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THESIS

16-INCH GUN-LAUNCHED ANTI-SATELLITE WEAPON

by

Joseph John Natale

June 1982

Thesis Advisor: A. E. Fuhs

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NAVAL POSTGRADUATE SCHOOL
Monterey, California

Rear Admiral J. J. Ekelund
Superintendent

David Schrady
Acting Provost

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William M. Tolles

W. M. Tolles
Dean of Research

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This thesis determined the feasibility of developing a 16-inch, gun-launched anti-satellite weapon. The general performance capability of rocket-and scramjet-boosted, gun-launched vehicles is examined with regards to propelling a miniature homing vehicle to a satellite intercept altitude. Rocket and scramjet boost vehicle performance is modeled and optimum trajectories are determined. A low gun elevation at launch and a pop-up manuever

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16-Inch Gun-Launched Anti-Satellite Weapon

by

Joseph John Natale
Lieutenant, United States Navy
B.A., University of California, Los Angeles, 1975

Submitted in partial fulfillment of the
requirement for the degree of

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June 1982

Author: Joseph J. Natale

Approved by: Allen E. Fuhs
Thesis Advisor

Daniel J. Collins
Chairman, Department of Aeronautics

William M. Tolles
Dean of Science and Engineering

ABSTRACT

This thesis determines the feasibility of developing a 16-inch, gun-launched anti-satellite weapon. The general performance capability of rocket-and scramjet-boosted, gun-launched vehicles is examined with regards to propelling a miniature homing vehicle to a satellite intercept altitude. Rocket and scramjet boost vehicle performance is modeled and optimum trajectories are determined. A low gun elevation at launch and a pop-up manuever are required to maximize the scramjet boost vehicle acceleration potential. The rocket boost vehicle is capable of intercepting a low altitude satellite without a pop-up manuever from a gun elevation of 45 degrees. Both boost methods provide apogees consistent with the intercept of known Soviet Electronic Intelligence Ocean Reconnaissance satellites, EORSAT, and Radar Ocean Reconnaissance satellites, RORSAT.

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I. INTRODUCTION

There are four events which suggest that a feasibility study should be made of the 16-inch naval gun as an anti-satellite, ASAT vehicle launcher. The first event is the paper by A. M. Valenti, Sannu Molder and G. R. Salter [Ref. 1] which indicates that a gun-launched supersonic-combustion ramjet, scramjet, is capable of 50-g acceleration and Mach 15 velocity. There is also the paper by C. H. Murphy, G. V. Bull and E. D. Boyer [Ref. 2] which indicates that a gun-launched rocket is capable of placing a payload in a highly elliptical 19,000 nm by 500 nm orbit. The second event is the U.S. Air Force development of a rocket-propelled, miniature ASAT weapon to be launched from the F-15 aircraft [Ref. 3]. The third event is the recommissiong of at least one Iowa class Battleship, consequently bringing nine 16-inch guns into service. The fourth event is the proliferation of long range anti-ship cruise missiles. To survive, a Naval Task Group must deny the enemy over-the-horizon targeting information provided by Ocean Surveillance Satellites [Ref. 4].

The USAF ASAT system involves the placement of a Miniature Vehicle, MV, which is a highly sophisticated homing weapon, in a sub-orbital acquisition window [Ref. 3]. The problem is, can a 16-inch, gun-launched vehicle place this or a similar MV ASAT weapon in the required sub-orbital acquisition window?

II. BACKGROUND AND DEVELOPMENT

A. THE MINIATURE ANTI-SATELLITE VEHICLE

Aviation Week [Ref. 3] describes the USAF ASAT as:

> Miniature vehicle anti-satellite weapon under development by the U.S. AIR FORCE SPACE DIV and Vought would utilize long wave infrared homing combined with laser-gyro stabilization and an extensive lateral maneuvering capability to collide with and destroy a hostile Soviet spacecraft.[p. 243]

The Air Force system actually uses the F-15 aircraft as a first stage; a Boeing short-range attack missile (SRAM) and a Vought Altair are used as second and third stage vehicles. The F-15 flies to a predetermined position and altitude and launches the SRAM-Altair-MV vehicle. The SRAM provides the majority of accelration. The second stage Altair spins the MV to 20 revolutions a second. After the target has been acquired by the MV, the MV is released by the Altair. The MV is described as being approximately 12 x 13 inches in size. [Ref. 3]

B. THE 16-INCH, 50-CALIBER NAVAL GUN

The 16-inch, 50-caliber naval gun, like the nine aboard the USS NEW JERSEY, has a 16-inch diameter bore. The barrel is approximately 66 feet long. The maximum gun elevation is 45 degrees. Standard projectiles weigh about 2700 pounds with a typical muzzle velocity of 2800 feet per second [Ref. 5]. The values above vary with charge and projectile weight.

Performance of the 16-inch gun when projectiles with smaller mass are used can be predicted. Assuming a frictionless barrel, which should be *nearly feasible* with silicon or teflon coated projectiles,

$$U = \left(\frac{P}{m} 2AL \right)^{1/2} \tag{1}$$

P = average pressure on the base of the projectile
m = mass of the projectile
A = base area of projectile
L = length of barrel
U = muzzle velocity

Using $P = 1.58562 \times 10^8$ N/m^2 or 23,000 lbf/in^2, $A = 0.1297$ m^2, and $L = 20.32$ m, the Mach number as a function of projectile mass is:

$$M = \left(\frac{8.3578 \times 10^8}{m}\right)^{1/2} \times \frac{1}{340.3} \tag{2}$$

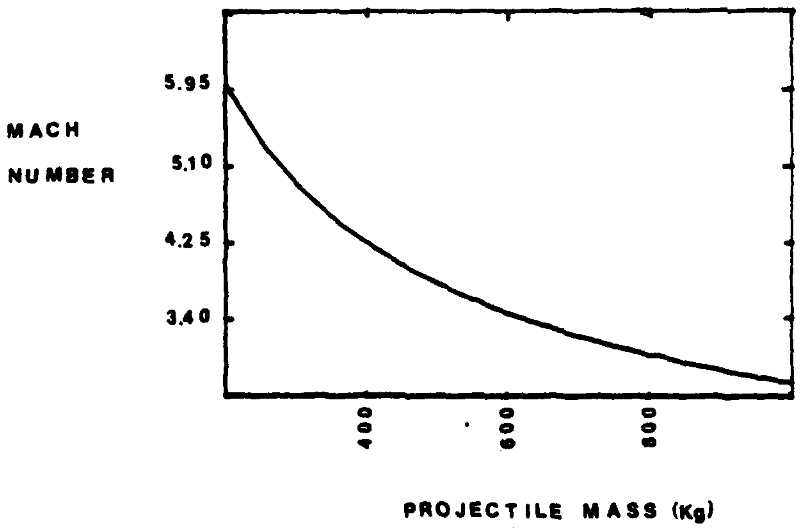

Fig. 1: MUZZLE MACH NUMBER VS. PROJECTILE MASS

The results of Figure 1 are substantiated by D. Monetta [Ref. 6].

C. 16-INCH GUN ASAT WEAPON

1. Target Altitudes

Ocean reconnaissance and targeting satellites are presumedly the primary targets for a Naval ASAT system [Ref. 3]. Their ability to locate and identify ships simplifies the Soviet over-the-horizon targeting problem. The Soviet RORSAT, Radar Ocean Reconnaissance Satellite, orbits at an altitude between 250 Km and 260 Km. The Soviet EORSAT, Electronic Intelligence Ocean Reconnaissance Satellite, orbits at an altitude between 430 Km and 440 Km [Ref. 4]. The altitude achieved by the gun-launched ASAT should be sufficient to intercept these satellites.

2. Mission Profile

Figure 2 depicts a possible 16-inch gun-launched ASAT mission profile. The 16-inch gun performs the function of a first stage booster, accelerating the boost vehicle, which includes the miniature ASAT vehicle, MV, to a velocity between Mach 3 and Mach 5. The boost vehicle should accelerate to a velocity between Mach 7 and Mach 9 and increase the flight path angle as measured from the horizontal to between 50 and 85 degrees. The MV and support equipment will detach from the boost vehicle at 150 Km. As the MV approaches the apogee, target acquisition occurs and lateral guidance corrections are made as necessary to achieve an intercept [Ref. 3].

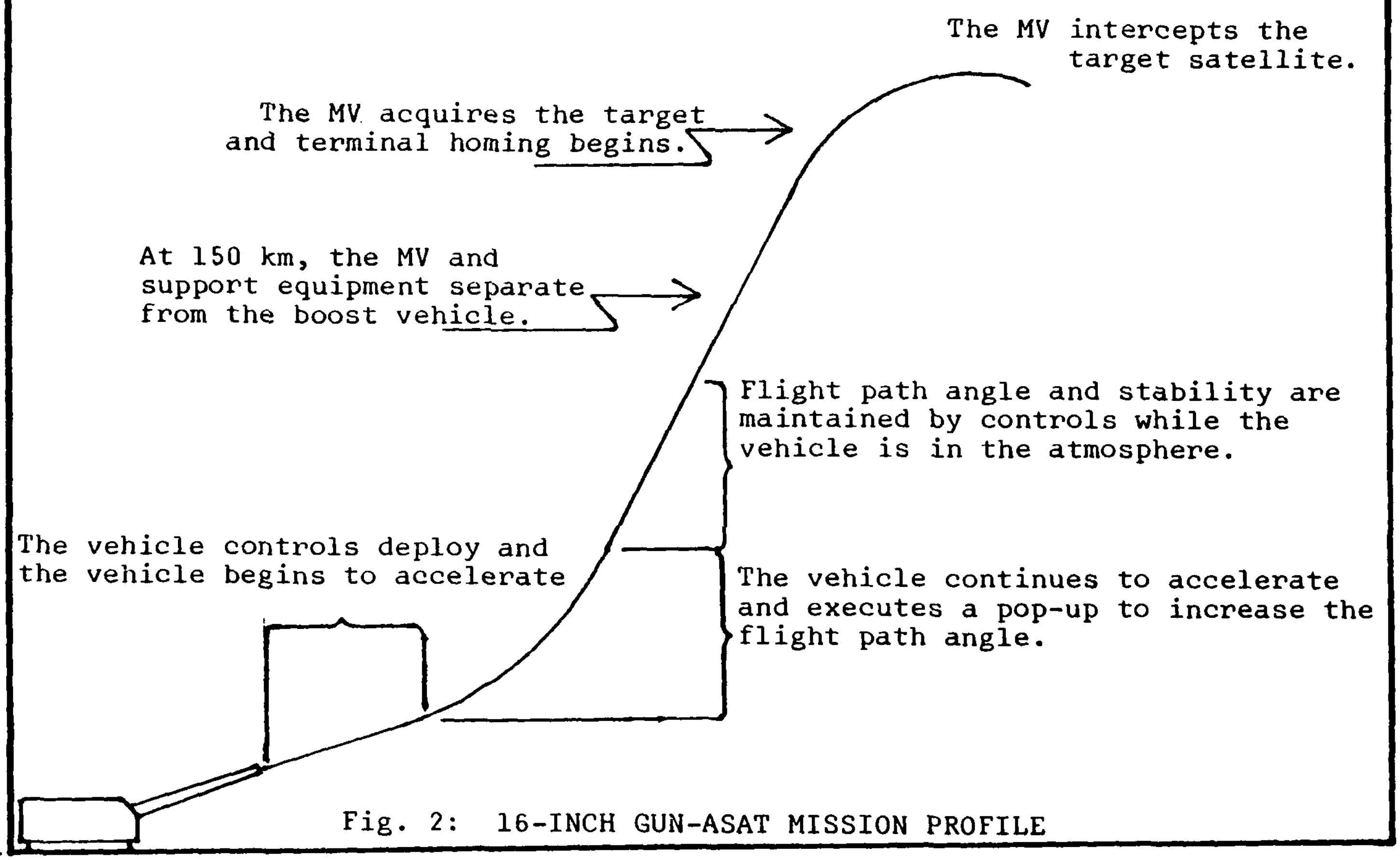

Fig. 2: 16-INCH GUN-ASAT MISSION PROFILE

3. Physical Characteristics

The boost vehicle may have a diameter as large as 16.5 inches if the gun is fitted with a smooth bore liner. A smooth bore in one of the nine 16-inch barrels on the Iowa class Battleship would not significantly degrade the ship's firepower. A smooth bore gun may also find additional applications with gun launched guided projectiles.

The vehicle may be sub-caliber if saboted; however, a sub-caliber vehicle with a diameter less than 14 inches will not accommodate the existing MV. The length of the vehicle is governed by the amount of handling room in the gun turret, by the barrel length and by the ability of the vehicle structure to withstand loading due to acceleration in the gun. The standard 16-inch projectile is approximately 80 inches long. Assuming the boost vehicle can be sectioned and assembled while being loaded into the gun, it could reasonably be 192 inches long [Ref. 2]. Acceleration within the barrel will range from 2600-g's to 7200-g's. The duration of this peak loading is from 0.04 to 0.02 seconds. If 120% yield stress is used as a working stress, it is reasonable to predict that 50 - 75% of the vehicle weight will be required for the structure [Ref. 1].

III. BOOST VEHICLE

The compatability of the boost vehicle with the 16-inch gun-launcher dictates many of the vehicle characteristics. Primarily, the vehicle is volume limited. The vehicle mass is also a key factor. The vehicle mass, as in any missile, is a function of payload, fuel, structure and controls; however, in this specialized application, mass also affects the muzzle velocity, V_0. Assuming vehicle with a mass of 350 Kg is used, the V_0 obtainable is 1360 m/sec, which is Mach 4.5. For the EORSAT mission, the intercept trajectory requires the vehicle to be at a velocity of 2618 m/sec, V, at 10 Km altitude. To achieve the required velocity, the vehicle must be capable of 7.9-g's of acceleration, A.

$$\frac{A}{g_0} = \frac{(V-V_0)^2}{2g_0 h} \tag{3}$$

Muzzle velocity may be increased, thereby reducing the acceleration requirements. However, an increase in V_0 is at the expense of fuel and/or payload. The required strength and consequently the mass of the vehicle case can only increase with increased V_0.

The majority of the air breathing engines are not applicable as a result of their inherent performance limitations. This includes the subsonic combustion ramjet, due to a low

acceleration limit. The supersonic combustion ramjet, scramjet, is, however, theoretically capable of 50-g acceleration [Ref. 1].

Solid or liquid fuel rockets of single-or multi-stage design are a second potential souce of propulsion.

A. SCRAMJET

1. Scramjet Background

Considerable research was focused on scramjets during the late 60's and early 70's. This included the testing of a Mach 7.0 gun-launched scramjet in 1975 [Ref. 7]. The detailed analysis required to develop a completely accurate model of a scarmjet is beyond the scope of this thesis. Therefore, various assumptions are made to simplify the scramjet model. The goal is to first determine system feasibility and to second identify areas requiring additional study.

2. Scramjet Model

The first assumption in this model is that γ, the ratio of the heat capacities, is constant and equal to 1.4 throughout the scramjet. Admittedly this is an erroneous assumption as the temperatures and pressures involved exceed the realm of ideal gas. Never-the-less the straight-forward evaluation allowed by the use of equations for ideal gas provides an optimistic, yet relevant, performance base-line for overall scramjet boosted ASAT system evaluation.

The scramjet was modeled in two sections, inlet and combustor. The nozzle is assumbed to be capable of expanding the flow to the ambient pressure, P_0, at all altitudes. The inlet is assumed to have variable geometry which will maintain a constant ratio of M_3/M_0 for all values of M_0. This performance characteristic is assumed to be achievable and is derived to maximize the thrust [Ref. 8]. The design of this inlet may, in fact, not be feasible and is an area requiring additional study.

a. Combustor

As shown in Figure 3, air enters the combustor at point 3 at some Mach number, M_3. M_3 is a function of the free stream Mach number, M_0, the kinetic energy efficiency of the diffuser, η_d, and some stagnation pressure, P_{T3}. P_{T3} is a function of the ratio of P_{T3}/P_{T0}, π_d. If $P_{T3}/P_{T0} = \pi_d$, $P_{T5}/P_{T3} = \pi_b$ and $P_{T6}/P_{T5} = \pi_n$ and complete expansion is assumed in the nozzle, then

$$\frac{P_{T6}}{P_{T0}} = \pi_n \times \pi_b \times \pi_d \tag{4}$$

Static and stagnation pressures at entrance and exit are related by

$$P_6 = P_0 = \frac{P_{T6}}{[1+\frac{\gamma-1}{2} M_6{}^2]^{\frac{\gamma}{\gamma-1}}} = \frac{P_{T0}}{[1+\frac{\gamma-1}{2} M_0{}^2]^{\frac{\gamma}{\gamma-1}}} \tag{5}$$

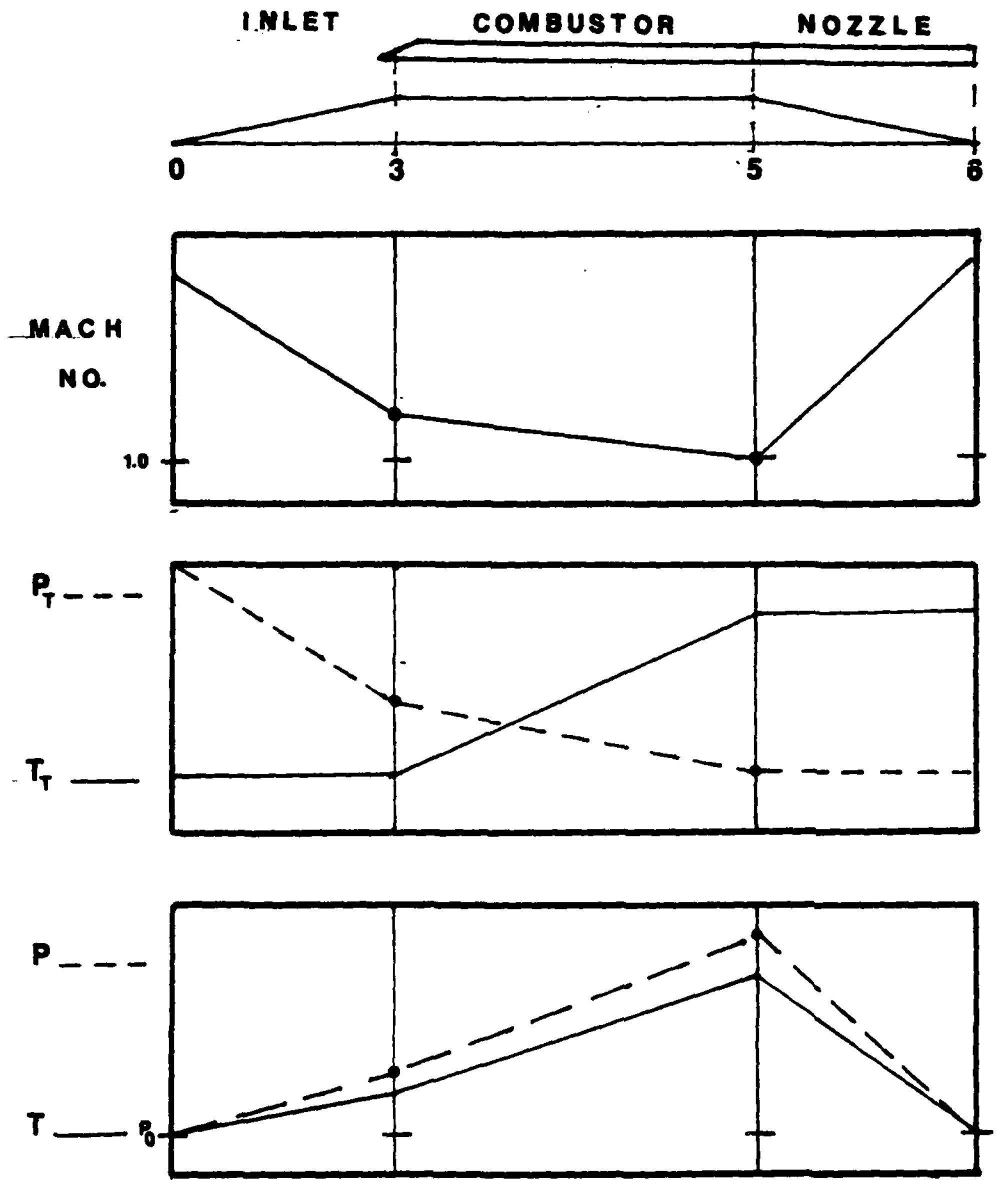

Fig. 3: IDEAL SCRAMJET CHARACTERISTICS
NOT DRAWN TO SCALE

From equations (4) and (5):

$$\frac{P_{T0}(\pi_n\ \pi_b\ \pi_b)}{[1+\frac{\gamma-1}{2}\ M_6^{\ 2}]^{\frac{\gamma}{\gamma-1}}} = \frac{P_{T0}}{[1+\frac{\gamma-1}{2}\ M_0^{\ 2}]^{\frac{\gamma}{\gamma-1}}} \tag{6}$$

Let

$$\pi = [\pi_n\ \pi_b\ \pi_d]^{\frac{\gamma-1}{\gamma}} = \frac{1+\frac{\gamma-1}{\gamma}\ M_6^{\ 2}}{1+\frac{\gamma-1}{\gamma}\ M_0^{\ 2}} \tag{7}$$

and $TR = 1 + [(\gamma+1)/2]\ M_0^{\ 2}$.

Solving equation (7) for $(M_6/M_0)^2$ and relating Mach number and temperatures, results in equation (8).

$$(\frac{M_6}{M_0})^2 = (\frac{V_6}{V_0})^2)\ \frac{T_0}{T_6} = \frac{1}{TR-1}\ (TR\cdot\pi-1) \tag{8}$$

The energy equation across the combustor is

$$\dot{Q} + \sum_{inlet} \dot{m}_i h_{Ti} = \sum_{exhaust} \dot{m}_e\ h_{Te} \tag{9}$$

where $\dot{Q}$ = [fuel flow rate]x[chemical energy of the fuel (h_f, BTU/lbm)]x[the combustion efficiency (η_b)]. Applying the definitions above to the energy equation produces equation (10).

$$f\ h_f\ \eta_b + h_{T3} = (1+f)\ h_{T6} \tag{10}$$

By relating the stagnation temperature to the enthalpy by $h_T = C_P T_T$, and solving for the fuel-air ratio, f, equations (11) and (12) may be written as:

$$C_P T_{T0} = f\ h_f\ \eta_b = (1+f) C_P T_{T6} \tag{11}$$

$$f = \frac{\frac{T_{T5}}{T_{T0}} - 1}{\frac{h_f \eta_b}{C_P T_{T0}} - \frac{T_{T5}}{T_{T0}}} \tag{12}$$

As indicated in Figure 3, the stagnation temperature, T_T, at point 0 is equal to the stagnation temperature at point 3, therefore, from equation (12):

$$\frac{T_{T5}}{T_{T0}} = \frac{T_{T5}}{T_{T3}} = 1 + \frac{f h_f \eta_b (1+f)}{C_P T_{T0}} \tag{13}$$

Solving for the Mach number at point 5 from equation (13):

$$M_5^{\ 2} = \frac{(1-2\gamma M_3^{\ 2}K) + \sqrt{1-2KM_3^{\ 2}(\gamma+1)}}{(2M_3^{\ 2}\gamma^2 K-\gamma-1)} \tag{14}$$

where

$$K = \frac{T_{T5}}{T_{T0}} \left(\frac{1+\frac{\gamma-1}{2} M_3^{\ 2}}{(1+\gamma M_3^{\ 2})^2} \right) \tag{15}$$

Now π_b may be expressed as:

$$\pi_b = \frac{P_{T5}}{P_{T3}} = \frac{1+\gamma M_3^{\ 2}}{1+\gamma M_5^{\ 2}} \left(\frac{1+\frac{\gamma-1}{2}M_5^{\ 2}}{1+\frac{\gamma-1}{2}M_3^{\ 2}} \right)^{\frac{\gamma}{\gamma-1}} \tag{16}$$

In evaluating π_d, the kinetic energy efficiency of the diffuser, η_d, is defined by stream velocity at point 3, V_3, divided by the free stream velocity, V_0, quantity squared. This assumes isentropic expansion to the free stream pressure P_0 for a given h_{T3} and P_{T3} [Ref. 8]. As developed by G. L. Dugger [Ref. 8], given M_3, P_{T3} may be determined from:

$$\eta_d = 1 - \frac{\left(\frac{P_{T0}}{P_{T3}}\right)^{\frac{\gamma-1}{\gamma}} - 1}{\left(\frac{\gamma-1}{2} M_0^2\right)}$$

Therefore π_d may be expressed as:

$$\pi_d = \left(1 + \frac{\gamma-1}{2} M_0^2 (1-\eta_d)\right)^{-\left(\frac{\gamma}{\gamma-1}\right)} \tag{17}$$

P_{T6}/P_{T5}, π_n, is assumed to be equal to 0.9.

$$F = \dot{m}_6 V_6 - \dot{m}_0 V_0 + A_6 (P_6 - P_0) \tag{18}$$

The general equation of thrust for an air breathing engine, above, may be written as equation (22) by assuming complete expansion in the nozzle such that $P_6 = P_0$. Then writing F as,

$$F = \dot{m}_0 V_0 \left(\frac{\dot{m}_6 V_6}{\dot{m}_0 V_0} - 1\right) \tag{19}$$

and noting that from equation (8)

$$\frac{V_6}{V_0} = \frac{M_6}{M_0} \sqrt{\frac{T_6}{T_0}} = \sqrt{\frac{1}{TR-1} (TR \cdot \pi - 1) \frac{T_6}{T_0}} \tag{20}$$

$\dot{m}_6 = \dot{m}_{air} + \dot{m}_{fuel}$ such that $\dot{m}_6/\dot{m}_0 = (1+f)$ by definition. Substituting equations (13) and (7) into the expression for T_6/T_0 in terms of stagnation temperature results in:

$$\frac{T_6}{T_0} = \frac{1 + \dfrac{f\, h_f \eta_b}{C_P T_{T0}}}{\pi(1+f)} \tag{21}$$

Combining and simplifying equation (19), (20), and (21) results in equation (22).

$$F = \dot{m}_0 V_0 \left(\sqrt{\frac{(1+f)(TR\cdot\pi-1)(1+\frac{f\eta_b h_f}{C_P T_{T0}})}{\pi(TR-1)}} -1\right) \tag{22}$$

Equation (22) is the expression for thrust produced by a scramjet as a function of M_0, M_3, losses in the engine π, f, η_b, h_f, $\dot{m}_0$, and T_{T0}.

The equations for thrust as a function of altitude M_0 and M_3, were programmed for a TI-59 calculator. See Appendix A for program listing. The atmospheric variable, ρ_0 (air density lbm/ft^3), T_0 (static air temperature, °R) and a_0 (sonic velocity, ft/sec) were entered for each altitude from tables of the ICAO STANDARD ATMOSPHERE [Ref. 9].

Though liquid hydrogen would provide a greater I_{sp}, a carbon-based fuel is used in this model. Carbon-based

fuels, like JP-5, $C_{10}H_{19}$, may be easily adapted to shipboard storage and have a significant density advantage over liquid hydrogen. The density of the fuel utilized is critical in this volume-limited system. The h_f used in these calculations is 18630 Btu/lbm. The flame temperature in the combustor, T_5, for JP-5 in air at 1500°R and 40 atmospheres is approximately 5000°R. The air temperature and pressure are approximations for conditions of point 3 when M_0 is Mach 6 at sea level. The theoretical stoichiometric f for JP-5 is 0.0687; f for the maximum flame temperature above is 0.0733. The flame temperature, T_5, of 5000°R is used as a limiting factor in the thrust equation.

The thrust program, illustrated in Figure 4 and summarized in Table I, is a decremental-loop program which decrements the value of f and then determines; one, if M_5 can be calculated; two, if M_5 is approximately equal to 1.0; and three, if T_5 is within the limits for combustion of JP-5. Failure of any of the three tests results in a reduction of f and another attempt at calculating the thrust. The test for $M_5 \geq 1$ causes the thrust to be determined for thermally choked flow at point 5. Thermally choked flow for a constant area combustor provides maximum thrust and over-all engine efficiency [Ref. 8].

b. Inlet

A significant factor governing the amount of thrust produced is the Mach number of the flow at point 3,

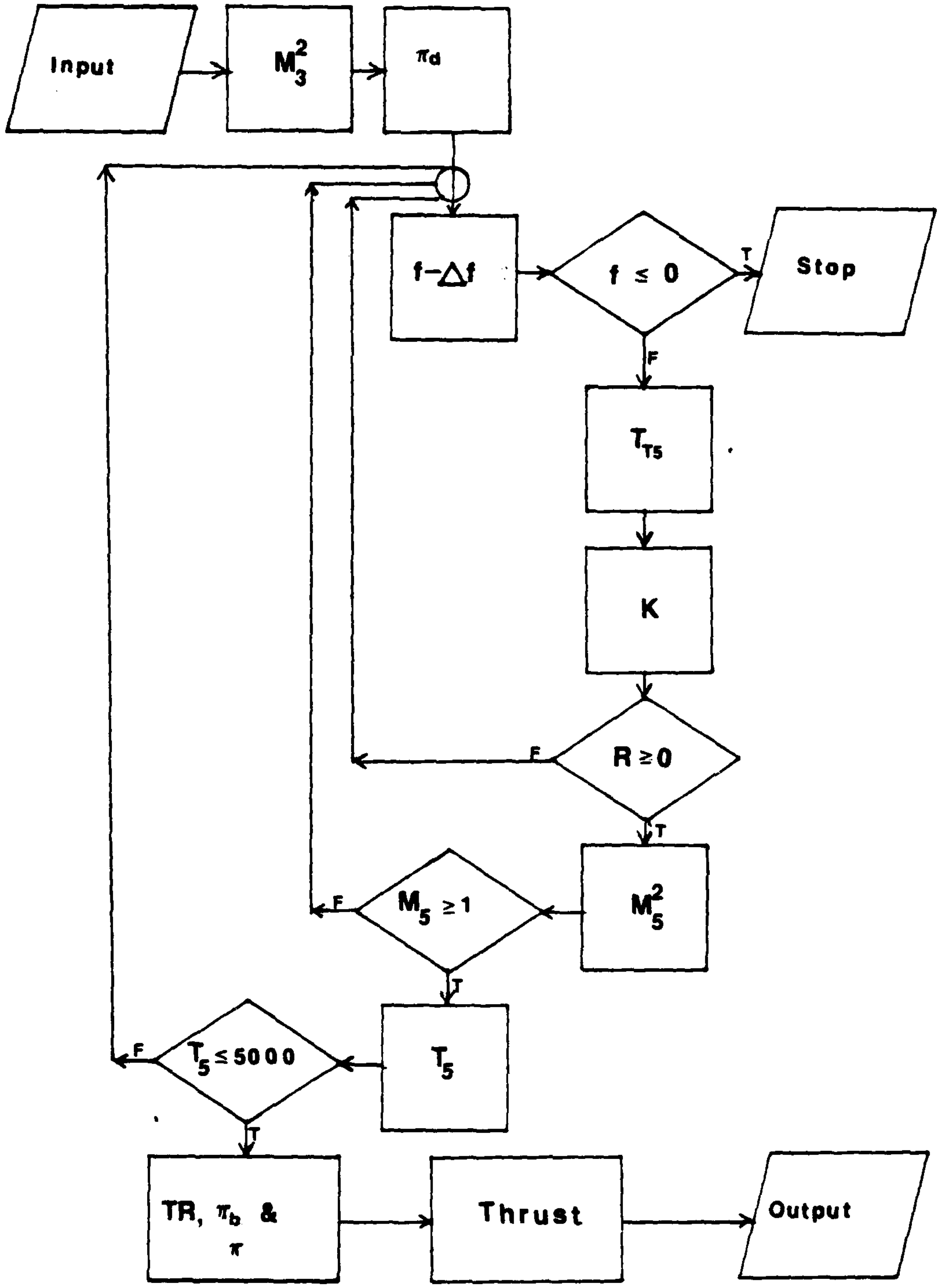

Fig. 4: SCRAMJET THRUST PROGRAM, LOGIC FLOW CHART

TABLE I

SUMMARY OF SCRAMJET THRUST PROGRAM EQUATIONS

$$\pi_d = (1+0.2M_0^{\,2}(1-\eta_d)^{3.5}$$

$$M_3 = 0.7M_0$$

$$\eta_b = 0.982$$

$$T_{T5} = \frac{(f\ 76950+T_{T0})}{(1+f)}$$

$$K = (\frac{T_{T5}}{T_{T0}})\ (\frac{1+0.2M_3^{\,2}}{(1+1.4M_3^{\,2})^2})$$

$$R = (1-4.8KM_3^{\,2})$$

$$M_5 = \sqrt{\frac{2.8M_3^{\,2}K-1-\sqrt{R})}{(0.4-3.92M_3^{\,2}K)}}$$

$$TR = (1+0.2M_0^{\,2})$$

$$\pi_b = \frac{(1+1.4M_3^{\,2})}{(1+1.4M_5^{\,2})}\ [\ \frac{(1+0.2M_5^{\,2})}{(1+0.2M_3^{\,2})}\ ]^{3.5}$$

$$\pi = (\pi_n\ \pi_b\ \pi_d)^{0.286}$$

$$F = \rho_0 A V_0^{\,2}\ [\sqrt{\frac{(1+f)(TR\cdot\pi-1)(1+\frac{f\eta_b h_f}{C_P T_{T0}})}{\pi(TR-1)}}\ -1]$$

M_3. Thrust was maximized for this scramjet by calculating thrust as a function of M_3 for various values of M_0, see Figure 5. Thrust was found to be maximized when $M_3/M_0 \approx 0.7$. Figure 5 was determined for sea level; however, the results were determined to be reasonably consistent at various altitudes.

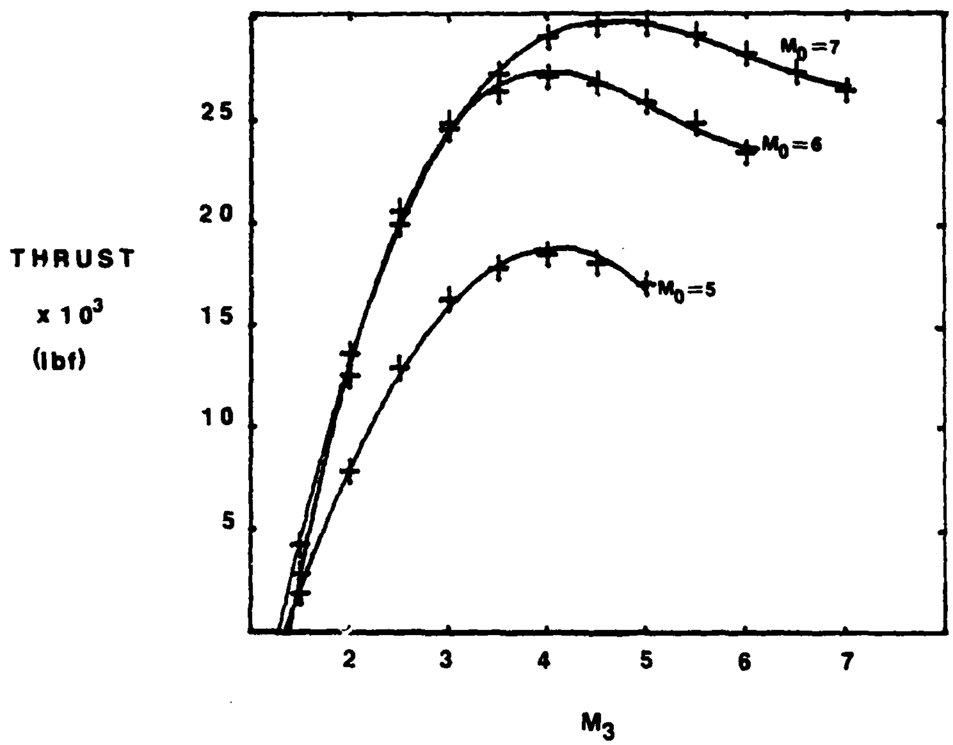

Fig. 5: SCRAMJET THRUST AS A FUNCTION OF THE MACH NUMBER AT POINT 3, M_3

The kinetic efficiency of the diffuser η_d was determined with the equation $\eta_d = 0.94 + 0.06M_3/M_0$. This

equation assumes perfect air through a 3 oblique shock inlet with wedge angles of 10 to 15 degrees for Mach numbers from 3.0 to 7.0 [Ref. 8].

c. Scramjet Thrust Data

The thrust produced by the scramjet was calculated as a function of M_0 and altitude with the following variables set to the values indicated:

$\eta_d = 0.982$

$A = 1.2$ (ft^2) inlet area

$\eta_n = 0.90$

T_5 (MAX) = 5000°R

$h_f = 18630$ (Btu/lbm)

f (stoichiometric) = 0.0687

$\eta_b = 0.95$

$M_3 = 0.7M_0$

The results are presented in Appendix B.

d. Curve Fit for Scramjet Performance

Calculation of the boost vehicle performance requires the values for thrust and fuel flow at each point along the flight path. The increment loop nature of the thrust program makes its incorporation into a flight path program undesirable. Fortunately, the plots of thrust and f as a function of Mach number and altitude are adequately represented by a series of straight lines. Figure 6 presents the correlation between the calculated data points, which are

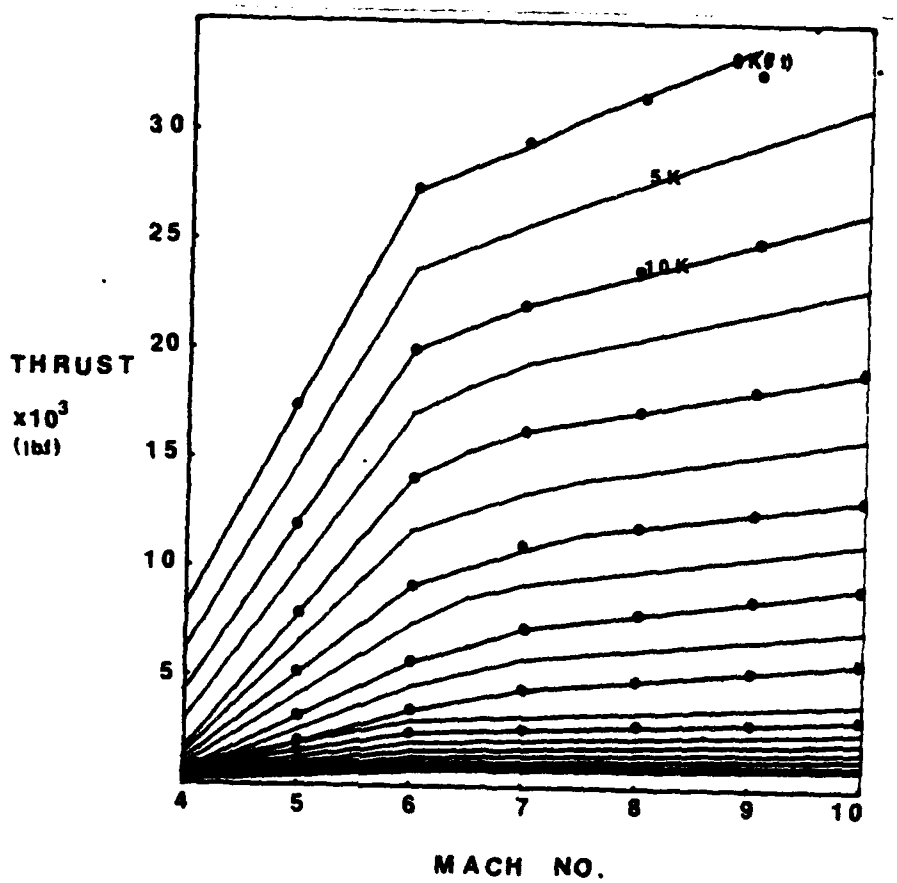

Fig. 6: SCRAMJET THRUST AS A FUNCTION OF MACH NUMBER AND ALTITUDE

shown as large dots calculated with the TI-59 thrust program, and the thrust curves calculated with the linear equations based on the thrust data. The linear equations for thrust are rather tedious and may be found in the program listing, Appendix C. The graph of f as a function of Mach number and altitude, shown in Figure 7, indicates that f may be approximated by three linear equations:

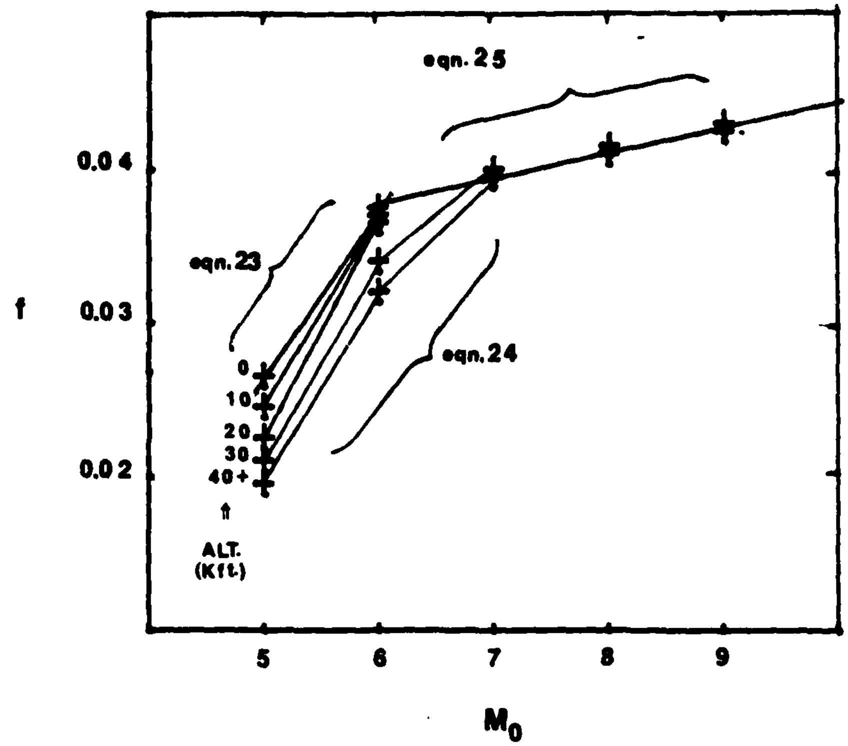

Fig. 7: FUEL-AIR RATIO, f, AS A FUNCTION OF THE MACH NUMBER AT POINT 0, M_0, AND ALTITUDE WITH CORRELATION TO APPROXIMATING EQUATIONS (23), (24), (25)

$$f = 0.011(M-5) + 0.0266 \quad \text{where } 4 \le M_0 < 6 \text{ and altitude} < 30{,}000 \text{ ft.} \tag{23}$$

$$f = 0.0093(M-5) + 0.021 \quad \text{where } 4 \le M_0 < 7 \text{ and altitude} > 30{,}000 \text{ ft.} \tag{24}$$

$$f = 0.0017(M-6) + 0.037 \quad \text{where 1) } M_0 > 6,\ \text{altitude} < 30{,}000 \text{ ft. } \; \text{2) } M_0 > 5,\ \text{altitude} > 30{,}000 \text{ ft.} \tag{25}$$

e. Scramjet Vehicle Design

A complete and thorough design for a gun-launched ASAT using a scramjet far exceeds the scope of this thesis. However a general dimensional presentation is required to determine aerodynamic characteristics as well as fuel and payload volume capacity.

The three-dimensional parameters that generally define the shape and size of the vehicle are outer diameter, inner diameter and length. The outer diameter is established by the gun which is 16 inches if the gun is unaltered and 16.5 if the rifling is removed. Total length assuming the capability of performing some assembly of diffuser and tail section in the gun turret should be a maximum of about 16 feet. The inner diameter refers to the diameter of the cylindrical inner body which houses the payload, fuel and the vehicle controls. The inner diameter (i.e., the diameter of the center body) is influenced by two factors. The first factor is a result of the design characteristics of the diffuser. A minimum area at point 3, A_3, exists with regards to the free stream capture area, A_0, and M_0. Continuing with the assumptions of ideal gas, $M_3/M_0 = 0.7$ and $\eta_d = 0.982$ the ratio A_3/A_0 may be obtained as follows: by continuity $\dot{m}_0 = \dot{m}_3$ such that $A_3/A_0 = (P_0/P_3)(M_0/M_3)(A_0/A_3)$. From the relationships for ideal gas the $T_{T0} = T_{T3}$, $P_{T0}/P_{T3} = 1/\pi_d$ the ratio of A_3/A_0 may be written as:

$$\frac{A_3}{A_0} = \frac{1}{\pi_d} \frac{M_0}{M_3} \left(\frac{1+\frac{\gamma-1}{2} M_3^2}{1+\frac{\gamma-1}{2} M_0^2} \right)^{(\frac{\gamma}{\gamma-1} - 1)} \tag{26}$$

Evaluating $1/\pi_d$ with equation (17) and applying the assumptions above, A_3/A_0 may be calculated as a function of M_0. At this point, an assumption must be made about the thickness of the outer case illustrated in Figure 8. Obviously, for a fixed A_0, the ratio of the diameter of the center body to free stream capture area, A_3/A_0, must decrease as the outer case thickness increases. Therefore, at least two options exist. The first option is to make the outer case thick enough to hold the fuel and controls. The second option minimizes the thickness of the outer case and carries all fuel and controls in the center body. The payload section will necessarily be located in the center body of the boost vehicle. The center body is required to be at least 13 inches in diameter to accommodate the existing ASAT MV or have sufficient volume to accommodate a volume-equivalent ASAT MV. Option two is therefore applicable.

If the outer case wall is assumed to be 0.5 inches thick, the area within the outer case is 176.7 square inches. For an A_0 of 153.9 square inches and flight Mach numbers of 4.5 to 9.0, A_3 will vary from 61.56 to 96.96 square inches.

Assuming the variable geometry of the inlet assembly is capable of reducing A_3 from its maximum to its

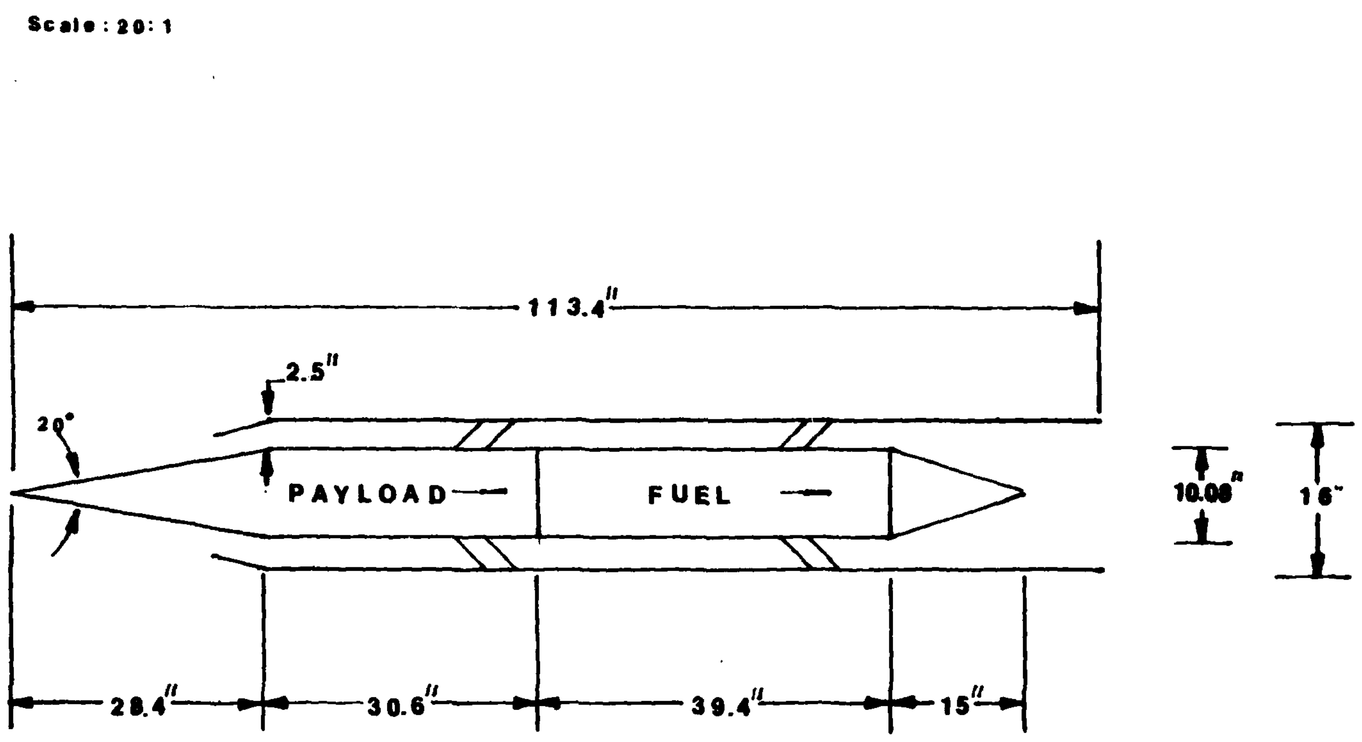

Fig. 8: GUN-LAUNCHED SCRAMJET ASAT WEAPON

minimum value, the maximum center body area must be small enough to provide for the maximum A_3. Consequently, the center body is limited to a 10.08 inch diameter.

As the dimensions of the center body will not accommodate the existing ASAT MV, a volume-equivalent payload of 2261 cubic inches will be used. This volume includes the 12 x 13 inch cylindrical MV and an additional 790 cubic inches of auxillary equipment.

Figure 8 is a general representation of a potential gun-launched scramjet ASAT vehicle. The volume equivalent payload will occupy the 309 cubic inches of the diffuser cone as well as a 30.6 inch section of the center body. This assumes 0.5 inch thick walls and a 10.08 inch diameter center body.

The scramjet engine was modeled using JP-5 as a typical fuel. JP-5 has a density of 0.0296 lbm/in^3. Therefore, to carry 100 lbm of fuel requires 3376.3 cubic inches; based on center body diameter, the volume corresponds to a 52.6 inch long section of center body. If a high density carbon based fuel, similar to the fuels being developed for various cruise missile applications, is used, a fuel density of 0.0397 lbm/in^3 may be assumed [Ref. 10]. The center body length required for fuel is then reduced to 39.4 inches. The vehicle case including structure and insulation is assumed to have an average density of 0.0367 lbm/in^3. The assumed total case mass is 356.33 lbm. Fuel

allotted is 110.23 lbm. The payload, which includes the MV, and support equipment, is allotted 100 lbm. Control and guidance equipment which includes diffuser control, fuel control and control surfaces actuators is allotted 15 lbm. Vehicle total launch weight is 716.5 lbm.

B. ROCKET

1. Rocket Background

Gun launched sounding rockets have been developed and tested as part of several projects. During the late 60's and early 70's, the Gun-Launched-Orbitor, (GLO-1A), was developed [Ref. 2]. The GLO-1A was a three stage system designed to be fired from a 16.7 inch, 75 caliber gun. The predicted apogee with a 8.6 lbm payload was 2629 nm. Applying this promising performance to the ASAT problem resulted in the following model.

2. Rocket Model

The rocket boosted gun-launched ASAT is a simple, single stage, fin-controlled system. The design assumes a smooth bore oversized gun barrel. The vehicle is assumed to be 16.5 inches in diameter. If a silicon greased nylon, or teflon obturator, is used, the barrel will be approximately 16.7 inches in diameter.

a. Rocket Thrust

The propellant grain is 40 x 16 inches, end inhibited, with an internal eight point star. A possible propellant is DB/AP-HMX/Al, which has a density of 0.067

lbm/in^3. The boost grain mass is 472.2 lbm or 216 Kg. For the purposes of this model, thrust is assumed to be constant and equal to the average thrust. The average thrust, T, is equal to 19010 lbf or 84556.48 Nt. The I_{sp} is 243 sec. Propellant mass burn rate is 78.7 lbm/sec or 36 Kg/sec. Assuming the action time equals the burn time, the boost grain is modeled to produce the average thrust for 6 seconds. The model also assumes complete expansion in the nozzle.

b. Rocket Vehicle Design

The diameter of the rocket boost vehicle will allow the use of the MV developed for the Air Force. As illustrated in Figure 9, a 12-inch long section of vehicle is allotted for the MV. Additionally, 2421 cubic inches are available in the nose cone for auxiliary equipment. The payload mass in the rocket system is the same as the scramjet system, 100 lbm. The weight of the vehicle case and controls, based on the values given for the GLO-1B [Ref. 2] is 184.4 lbm or 83.6 Kg. Total vehicle mass is 760.59 lbm or 345 Kg.

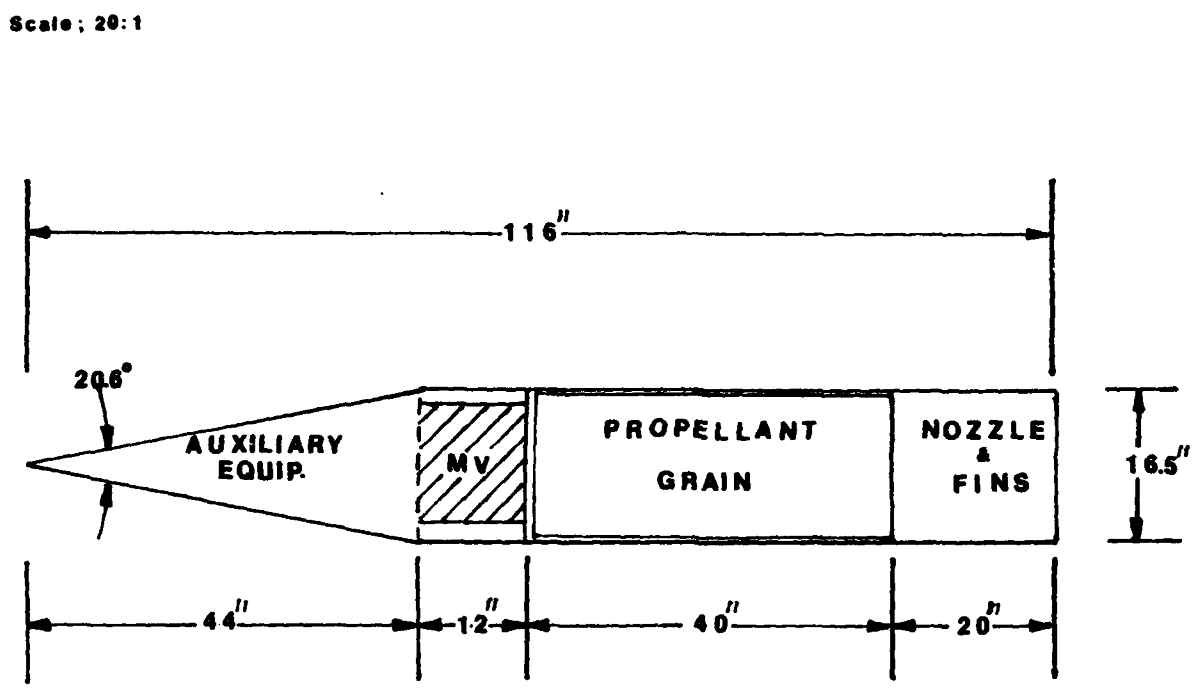

Fig. 9: GUN-LAUNCHED ROCKET ASAT WEAPON

IV. HYPERSONIC AERODYNAMICS

Both the scramjet and the rocket boost vehicles exit the barrel at a high supersonic Mach number, 4.5, and rapidly accelerate to hypersonic speeds greater than Mach 5. Both vehicles are basically cone capped cylinders. As indicated in Figure 2, in order to maximize performance, the vehicles will need to increase their flight path angle, A, from the maximum gun launch angle of 45 degrees. The variables used in this section are those used in the trajectory program of Appendix C. Aerodynamic lift is used to achieve the change in trajectory angle. The change in trajectory angle is termed a pop-up maneuver. Therefore, the aerodynamic control system for the vehicle must be capable of providing an angle of attack, A7, as well as stabilizing the vehicle.

A. HYPERSONIC AERODYNAMIC FORCES

One theoretical method of dealing with hypersonic aerodynamics is through the use of Newtonian impact theory. This entire section on hypersonic aerodynamics follows closely the presentation in Chapters 3 and 4 of Truitt [Ref. 11]. The basic assumption is that at extremely high Mach numbers the aerodynamic force coefficients are independent of the mach number. Aerodynamic forces on the body are a function of surface area presented to the free

stream. Comparison between impact theory predictions of force characteristics for a cone-cylinder body and experimental data at Mach 7 is of the same order of accuracy as obtained at lower Mach number with supersonic theory. Accuracy can be expected to increase with higher Mach numbers as the impact theory is derived for a free stream Mach number of infinity.

Three possible cases can be considered in determining the force coefficients for the body:

Case One - The angle of attack equals zero, A7 = 0.

Case Two - The angle of attack is less than or equal to the half cone angle, A7≤A3.

Case Three - The angle of attack is greater than the half cone angle, A7>A3.

Define the following symbols:

C_N = normal force coefficient

C_C = axial force coefficient

A3 = half cone angle (deg)

A7 = angle of attack (deg)

R9 = diameter of cone base = diameter of cylinder(inch)

L_{DL} = length of cone (inch)

L_{DS} = length of cone not considered for cowl (inch)

R0 = diameter of cowl opening (inch)

Using the cone shown in Figure 9, A_3 would be 10.3°.

1. Case One: A7 = 0

The cylinder is parallel to the free stream, therefore, $C_{N\ (Cyl)} = C_{C\ (Cyl)} = C_L = C_D = 0$. The cone presents a symmetrical surface to the free stream, therefore:

$$C_{C_{cone}} = 2\ \sin^2 A3 \tag{27}$$

The normal force coefficient is equal and opposite at each opposing point on the cone such that $C_{N(Cone)} = 0$.

2. Case Two: A7≤A3

In this case, the entire cone is presented to the flow such that:

$$C_{N_{cone}} = \cos^2 A3 \sin 2A7 \tag{28}$$

and

$$C_{C_{cone}} = 2\sin^2 A3 + \sin^2 A7\ (1-3\sin^2 A3) \tag{29}$$

3. Case Three: A7>A3

Only a portion of the cone is presented to the free stream forming a low pressure shadow over the remainder of the surface. The area subject to free stream impact is described by:

$$B = \arcsin\left(\frac{\tan A3}{\tan A7}\right) \tag{30}$$

Then

$$C_{N_{cone}} = \cos^2 A3 \sin A7 [\frac{B+\frac{\pi}{2}}{\pi} + \frac{1}{3\pi}$$

$$x \cos B(\cot A7 \tan A3 + 2\tan A7 \cot A3)] \qquad (31)$$

and

$$C_{C_{cone}} = 2\sin^2 A3 + \sin^2 A7(1-3\sin^2 A3)(\frac{B+\frac{\pi}{2}}{\pi})$$

$$+ \frac{3}{4\pi} \cos B \sin 2A7 \sin 2A3 \qquad (32)$$

For both cases two and three, the force coefficient on the cylinder are represented by $C_C = 0$ and

$$C_{N_{cyl}} = \frac{5.33}{\pi} \frac{L9}{R9} \sin^2 A7 \qquad (33)$$

Equations (27) through (33) effectively describe the hypersonic forces on the rocket boost vehicle. However, the scramjet configuration, neglecting the diffuser cone, is best represented by a partial cone and a cylinder. The partial cone represents the scramjet cowl.

In modelling the cowl consider the cone divided into two cones. As illustr. ted by Figure 10, the large cone has a length, L_{DL}, and a base diameter of R9. The small cone has a length, L_{DS}, and a base diameter of R0. The cowl is

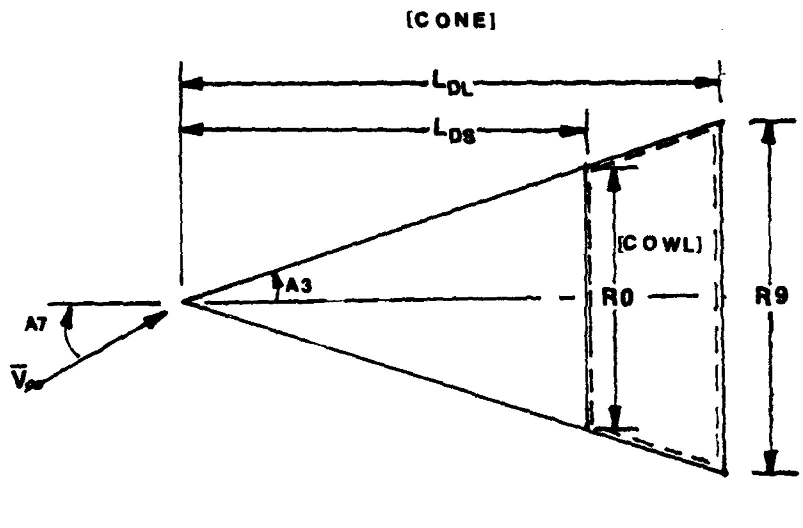

Fig. 10: CONE AND COWL

represented by the (large cone - small cone), and, therefore, has an inlet diameter of R0 and a base diameter of R9. Relating the C_N on the cones for case two by the base area;

$C_{N_{Small\ Cone}} = \cos^2 A3 \sin 2A7$; base area = $\pi/4(R0^2)$

$C_{N_{Large\ Cone}} = \cos^2 A3 \sin 2A7$; base area = $\pi/4(R9^2)$.

$$C_{N_{Cowl}} = C_{N_{Large\ Cone}} - C_{N_{Small\ Cone}} \tag{34}$$

Converting to a common base area

$$C_{N_{Small\ Cone}} \left(\frac{\pi R0^2}{4} \quad \frac{4}{\pi R9^2}\right) = \cos^2 A3 \sin 2A7 \tag{35}$$

The conversion factor for the forces on the cowl is:

$$(1 - (\frac{R0}{R9})^2) \tag{36}$$

4. C_D and C_L

By multiplying equations (27), (28), (29), (31), (32) and (33) by equation (36), $C_{N\ (cowl)}$ and $C_{C\ (cowl)}$ may be determined for each case.

The coefficients of lift, C_L, and drag, C_D, for the cowl or cone are expressed in terms of the applicable value of C_C and C_N. The general equations for C_D and C_L are:

Case One: $C_D = C_C = 2\sin^2 A3$ (27a)

Case Two and Case Three:

$$C_D = C_N \sin A7 + C_C \cos A7 \tag{37}$$

$$C_L = C_N \cos A7 - C_C \sin A7 \tag{38}$$

For the cylinder:

Case One: $C_D = C_N = C_C = 0$ (39)

Case Two and Case Three:

$$C_{D_{cyl}} = C_{N_{cyl}} \sin A7 \tag{40}$$

$$C_{L_{cyl}} = C_{N_{cyl}} \cos A7 \tag{41}$$

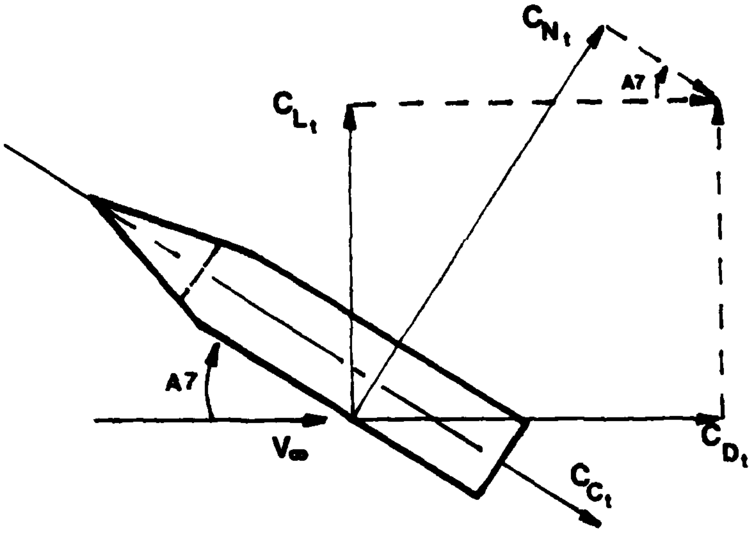

Fig. 11: AERODYNAMIC FORCE COEFFICIENTS

The total lift and drag coefficient due to the impact theory, as shown in Figure 11, is

$$C_{L_t} = C_L + C_{L_{cyl}} \tag{42}$$

$$C_{D_t} = C_D + C_{D_{cyl}} \tag{43}$$

In addition to impact drag, the coefficient of skin friction drag was determined for flow over the cylinder. The equations for skin friction as a result of laminar imcompressible flow over a flat plate were applied to a cylinder of length, L [Ref. 12].

$$C_{DF} = \frac{1.328\sqrt{\mu}}{\sqrt{\rho_0 V_o} L} \tag{44}$$

This model for boundary layer was selected to provide insight concerning magnitude of skin friction. A more refined analysis using theory appropriate for hypersonic flow is needed. Equation (43) then becomes:

$$C_{D_t} = C_D + C_{D_{cyl}} + C_{DF} \tag{43a}$$

B. CONTROLS

The control system on the vehicle must be capable of initiating and maintaining the required angle of attack to achieve and maintain the desired flight path angle until the vehicle is exoatmospheric. The flight path angle and velocity as the vehicle begins a vacuum trajectory will determine the apogee and the encounter geometry between the MV and the target satellite.

1. Forms of Control

There are two basic forms of control that may be used to control the vehicle, vectored thrust or aerodynamic control surfaces.

The vectored thrust approach could be achieved with external or internal reaction jets. The volume and weight

limitations of this system prevent the use of a separate engine to support the reaction jets. Therefore, the reaction jets would depend on bleed pressure from the booster. The rocket burns for only 6 seconds and the scramjet must burn most of its fuel at low altitudes for maximum efficiency. In both cases, there may be no thrust available for control while the vehicle is still subject to high dynamic pressures.

Two possible types of control surfaces are folding fins, similar to those used on the 5-inch guided projectile [Ref. 13], or storable flaps. The fins would fold at the base of the vehicle, adding to its length, and would deploy upon clearing the barrel.

The storable flap would be of the same contour as the vehicle body and would store flush with the body. The four evenly spaced flaps would be hinged on the forward edge with the rear edge elevated by an actuator. The effect would be similar to that of a variable geometry frustum. The advantage of the storable flap is that when control is not required, drag is not created by the control surface.

Any type of control surface used must be capable of withstanding the launch and up to 1,500,000 N/m^2 of in flight dynamic pressure.

V. TRAJECTORY OPTIMIZATION

The gun-launched ASAT system was modeled on a HP-9830 computer. See Appendix C for the program listing. The program is designed to calculate the vehicle position, altitude, acceleration, thrust, weight, drag and lift once each time increment, t. Either the scramjet or the rocket boost vehicle described previously may be selected. Gun elevation, A, pop-up altitude, H1, angle of attack, A7, and maximum flight path angle, A8, are input variables. Thrust, F, fuel/air ratio, F8, drag, D, and lift, L, are calculated at each time increment with the equations developed in the previous chapters. The trajectories assume a flat earth. If a maximum apogee of 1000 Km is assumed, the error between flat earth and round earth calculations is about ± 5%.

A. OPTIMUM SCRAMJET TRAJECTORY

The scramjet performance is related to the dynamic pressure. If the flight path is level and at a moderately low altitude, the scramjet is theoretically capable of rather phenomenal performance. As the flight path becomes steeper, and the vehicle rapidly gains altitude, the atmospheric oxygen available for combustion decreases. Therefore, the scramjet has less time to produce useful thrust. This makes the scramjet performance sensitive to the gun elevation angle, the pop-up altitude and the angle of attack.

A trial and error method was used to determine the optimum scramjet trajectory. The gun elevation angle was varied from 15 to 45 degrees in 5 degree increments. For each gun elevation angle, the angle of attack was varied from 0 to 12 degrees in 3 degree increments. This was done for various pop-up altitudes from 500 to 11,000 meters. The results are presented in Figure 12. The maximum apogee, 558 Km, results from a gun elevation angle of 15 degrees, a pop-up altitude of 6000 meters and an angle of attack of 12 degrees.

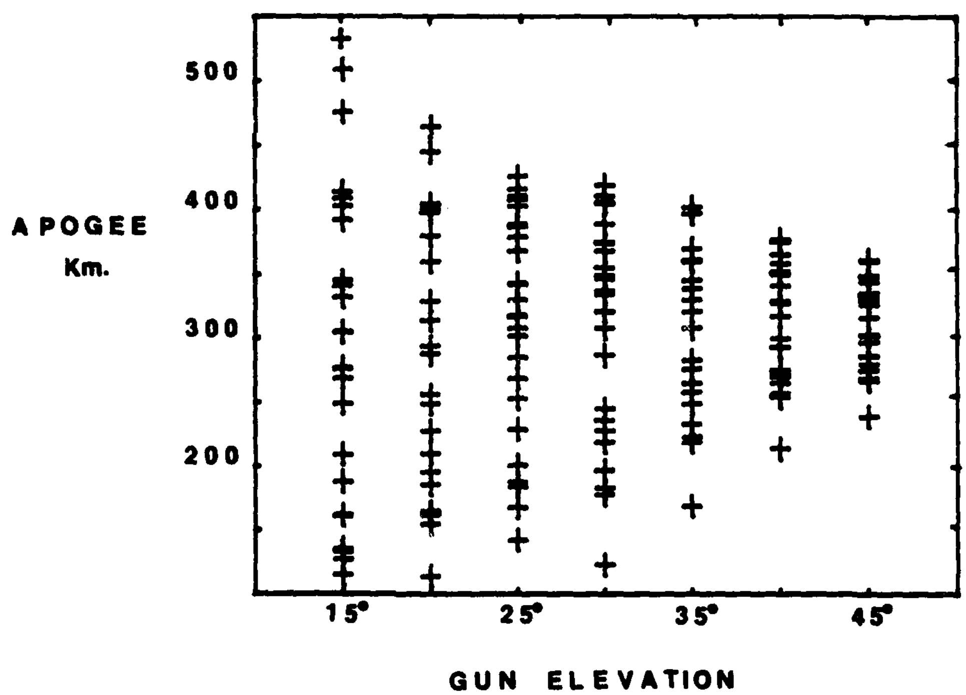

Fig. 12: SCRAMJET APOGEE AS A FUNCTION OF GUN ELEVATION FOR VARIOUS ANGLES OF ATTACK AND POP-UP ALTITUDES

The data spread indicates that as the gun elevation angle increases, the trajectory becomes less sensitive to the angle of attack and pop-up altitude. Appendix D presents the data used to produce Figure 12. Included are the angle of attack and pop-up altitude for each point.

Figures 13 and 14 represent the variation of apogee as a function of pop-up altitude and angle of attack at a given gun elevation.

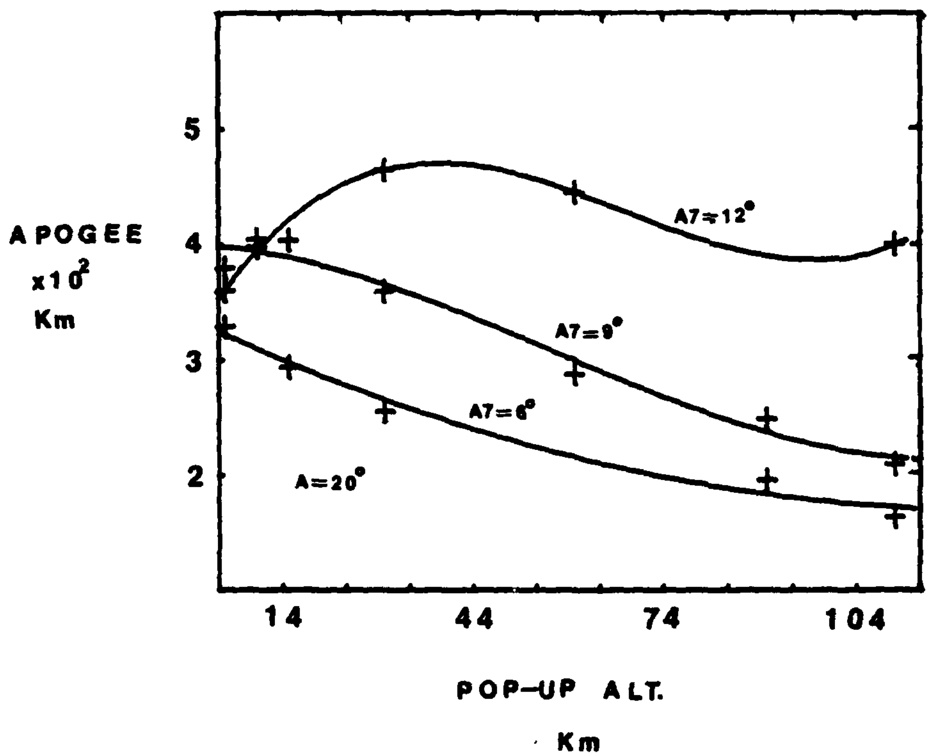

Fig. 13: SCRAMJET APOGEE AS A FUNCTION OF GUN ELEVATION, A, ANGLE OF ATTACK, A7, AND POP-UP ALTITUDE, A=20°

The A7 = 12° curve which appears in Figure 14, verifies the assumption that maximum performance for a gun elevation angle of 15 degrees and an angle of attack of 12 degrees occurs when the pop-up altitude is 6000 m.

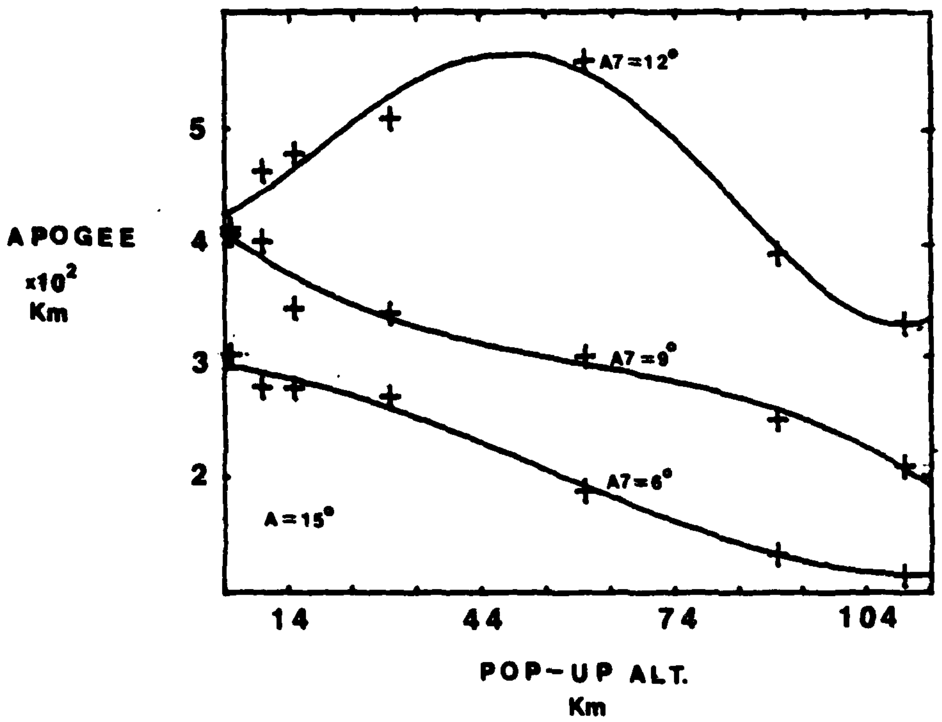

Fig. 14: SCRAMJET APOGEE AS A FUNCTION OF GUN ELEVATION, A, ANGLE OF ATTACK, A7, AND POP-UP ALTITUDE, A=15°

B. OPTIMUM ROCKET TRAJECTORY

Determination of the optimum rocket trajectory is straight forward, relative to determining the scramjet optimum trajectory. The forces affecting the rocket are thrust, drag, and gravity. Thrust is assumed constant and of a 6 second duration. Gravity varies little over the altitude range under study and is considered constant, $g = g_0$. Drag decreases with altitude. From acceleration = force/mass where force = $(\vec{thrust} - \vec{drag} - m\vec{g})$ and mass decreases with time, to increase acceleration, drag must be decreased while thrust is still present. Increasing altitude as rapidly as possible is the obvious solution. Ideally the gun would be elevated to 90 degrees and the rocket fired immediately upon leaving the barrel. As a gun elevation of 90 degrees is not possible, the next best solution is to use the maximum gun elevation angle, 45 degrees, and pop-up as soon as feasible after leaving the barrel. If the pop-up altitude is 1000 m and the muzzle velocity is Mach 4.5, there are 0.7 seconds for the control system to become operative and for the rocket to ignite. The apogee achieved under these conditions is 928 Km. Table 2 is a listing of apogee as a function of pop-up altitude and angle of attack. The gun elevation angle is 45 degrees. Of particular interest is the first entry in Table 2. A simple rocket-boosted, 45-degree launch with no pop-up is capable of propelling the 45 Kg paylog to an altitude of 409 Km. Table 2 also shows that the apogee is insensitive to pop-up altitude up to about 2000 m.

Figure 15 represents the maximum apogee trajectory of the gun-launched scramjet ASAT. The program output for this trajectory is found in Appendix E.

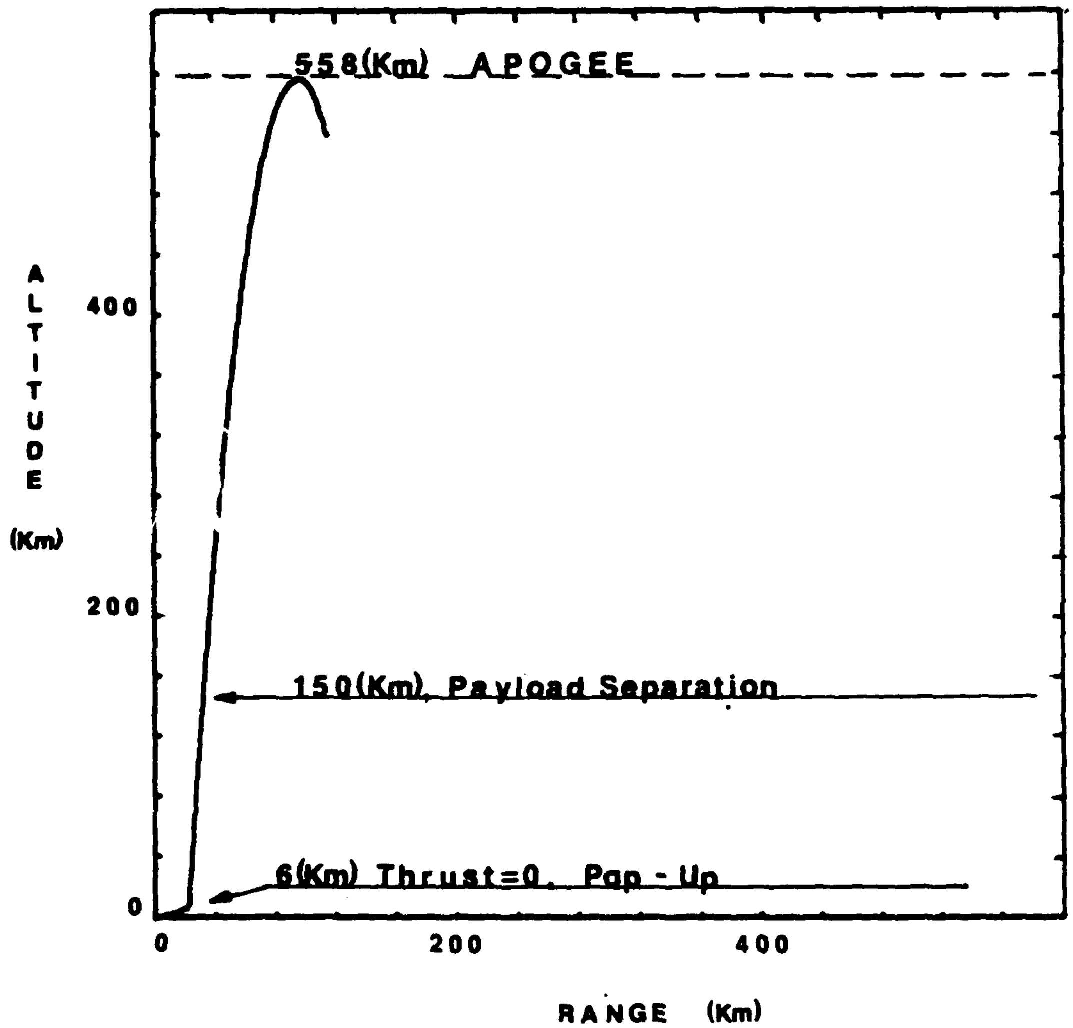

Fig. 15: SCRAMJET MAXIMUM APOGEE TRAJECTORY

TALBE II

APOGEE AS A FUNCTION OF ANGLE OF ATTACK AND POP-UP ALTITUDE FOR GUN-ELEVATION = 45°

Angle of Attack (DEG)	Pop-up Altitude (m)	Apogee (Km)
0	0	409
3	100	577
6	100	753
9	100	800
12	100	928
3	300	577
6	300	753
9	300	800
12	300	928
3	1000	577
6	1000	753
9	1000	800
12	1000	928
3	3000	554
6	3000	716
9	3000	774
12	3000	828
3	6000	531
6	6000	673
9	6000	743
12	6000	909

If a comparison is made of flight parameters at an arbitrary point, 100 Km, where the dynamic pressure can be assumed to be zero, the Mach number and flight path angle of a shot with an angle of attack of 3 degrees and a pop-up altitude of 100 - 1000 m, are 13.1 and 53.3 degrees. For the same shot with an angle of attack of 12 degrees the Mach number is 14.0 and the flight path angle is 81 degrees. By executing a 40-g pop-up, the vehicle avoids a great deal of drag and achieves greater acceleration, as previously assumed.

Figure 16 represents the maximum apogee trajectory of the gun-launched rocket ASAT. The program output for this trajectory is found in Appendix E.

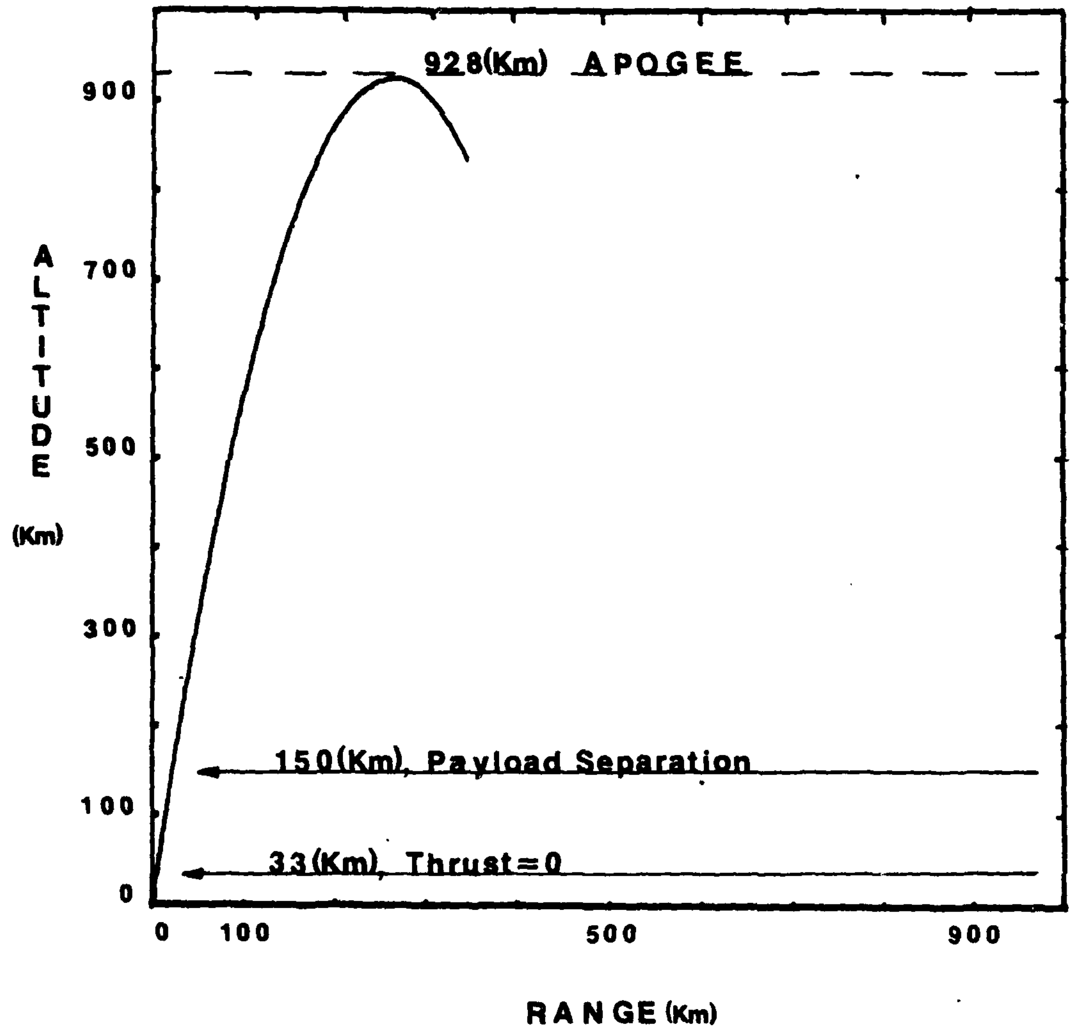

Fig. 16: ROCKET MAXIMUM APOGEE TRAJECTORY

VI. CONCLUSIONS

The design and development of a 16-inch gun-launched anti-satellite weapon is theoretically feasible. Given proper targeting information and assuming the MV can be configured for gun launching, a rocket or scramjet gun-launched vehicle can boost the ASAT payload to altitudes at which a RORSAT or EORSAT may be intercepted.

The air-breathing scramjet has a greater I_{sp} than does the rocket; however, the scramjet thrust is altitude limited. The rocket can take advantage of a farvorable thrust-to-drag ratio at higher altitudes.

The need for an inlet on the scramjet complicates payload placement and limits the volume available for fuel. The greater density of the rocket propellent better utilizes the volume available.

The rocket boost vehicle requires few advances in design technology, and the maximum apogee of 928 Km for the rocket ASAT with same payload as the scramjet ASAT indicates that heavier payloads may be delivered by a rocket ASAT to the altitudes of interest, 250 -440 Km. The ability of the rocket boost vehicle to intercept satellites up to 409 Km, without executing a pop-up manuever, indicates that a very simple, possible spin-stabilized vehicle, can be developed to counter the low altitude threat.

APPENDIX A

PROGRAM LISTING FOR SCRAMJET THRUST

This is a listing for a TI-59 program that will, for a given altitude, calculate the thrust for a scramjet. The program executes in a closed loop, calculating the thrust for the initial Mach number, incrementing the Mach number by one and recalculating the thrust.

The memory loading prior to execution of the program:

Memory	Variable	Value	Comment
03	η_d	0.97	
04	P_0	----	Air density (lbm/in^3)
06	A	1.24	inlet area (ft^2)
07	π_n	0.9	
09	h_f	18630	Btu/lbm
15	f	0.0676	
21	Δf	-0.0005	
25	T_0	----	static air temp. (°R)
26	a_0	----	sonic speed (ft/sec)

Place initial Mach number in register and press A' to execute.

000	76	LBL
001	11	A
002	53	(
003	01	1
004	85	+
005	93	.
006	02	2
007	65	×
008	43	RCL
009	02	02
010	33	X^2
011	65	×
012	53	(
013	01	1
014	75	-
015	43	RCL
016	03	03
017	54	)
018	54	)
019	45	Y^X
020	03	3
021	93	.
022	05	5
023	94	+/-
024	95	=
025	42	STO
026	13	13
027	68	NOP
028	43	RCL
029	02	02
030	65	×
031	93	.
032	07	7
033	95	=
034	33	X^2
035	42	STO
036	14	14
037	68	NOP
038	68	NOP
039	68	NOP
040	68	NOP
041	68	NOP
042	68	NOP
043	68	NOP
044	68	NOP
045	68	NOP
046	68	NOP
047	68	NOP
048	76	LBL
049	17	B'
050	43	RCL
051	21	21
052	44	SUM
053	15	15
054	25	CLR
055	32	X:T
056	43	RCL
057	15	15
058	22	INV
059	77	GE
060	19	D'
061	53	(
062	43	RCL
063	15	15
064	65	×
065	07	7
066	06	6
067	09	9
068	05	5
069	00	0
070	85	+
071	43	RCL
072	01	01
073	54	)
074	55	÷
075	53	(
076	01	1
077	85	+
078	43	RCL
079	15	15
080	54	)
081	95	=
082	42	STO
083	08	08
084	55	÷
085	43	RCL
086	01	01
087	95	=
088	65	×
089	53	(
090	01	1
091	85	+
092	93	.
093	02	2
094	65	×

```
095  43  RCL
096  14   14
097  54   )
098  95   =
099  55   ÷
100  53   (
101  53   (
102  01   1
103  85   +
104  01   1
105  93   .
106  04   4
107  65   ×
108  43  RCL
109  14   14
110  54   )
111  33  X²
112  54   )
113  95   =
114  42  STO
115  16   16
116  53   (
117  01   1
118  75   -
119  04   4
120  93   .
121  08   8
122  65   ×
123  43  RCL
124  16   16
125  65   ×
126  43  RCL
127  14   14
128  54   )
129  95   =
130  32  X:T
131  00   0
132  22  INV
133  77   GE
134  12   B
135  61  GTO
136  00   00
137  49   49
138  91  R/S
139  68  NOP
140  68  NOP
141  76  LBL
142  12   B
143  32  X:T
144  34  ΓX
145  94  +/-
146  85   +
147  53   (
148  02   2
149  93   .
150  08   8
151  65   ×
152  43  RCL
153  14   14
154  65   ×
155  43  RCL
156  16   16
157  75   -
158  01   1
159  54   )
160  95   =
161  55   ÷
162  53   (
163  93   .
164  04   4
165  75   -
166  03   3
167  93   .
168  09   9
169  02   2
170  65   ×
171  43  RCL
172  14   14
173  65   ×
174  43  RCL
175  16   16
176  54   )
177  95   =
178  34  ΓX
179  32  X:T
180  01   1
181  22  INV
182  77   GE
183  15   E
184  61  GTO
185  00   00
186  49   49
187  91  R/S
188  76  LBL
189  15   E
190  32  X:T
```

191	68	NOP
192	33	X²
193	42	STO
194	17	17
195	61	GTO
196	03	03
197	78	78
198	43	RCL
199	08	08
200	99	PRT
201	43	RCL
202	02	02
203	33	X²
204	65	×
205	93	.
206	02	2
207	85	+
208	01	1
209	95	=
210	42	STO
211	19	19
212	53	(
213	01	1
214	85	+
215	01	1
216	93	.
217	04	4
218	65	×
219	43	RCL
220	14	14
221	54	)
222	55	÷
223	53	(
224	01	1
225	85	+
226	01	1
227	93	.
228	04	4
229	65	×
230	43	RCL
231	17	17
232	54	)
233	95	=
234	65	×
235	53	(
236	53	(
237	53	(
238	01	1
239	85	+
240	93	.
241	02	2
242	65	×
243	43	RCL
244	17	17
245	54	)
246	55	÷
247	53	(
248	01	1
249	85	+
250	93	.
251	02	2
252	65	×
253	43	RCL
254	14	14
255	54	)
256	54	)
257	45	Yˣ
258	03	3
259	93	.
260	05	5
261	54	)
262	95	=
263	68	NOP
264	65	×
265	43	RCL
266	13	13
267	65	×
268	43	RCL
269	07	07
270	95	=
271	45	Yˣ
272	93	.
273	02	2
274	08	8
275	06	6
276	95	=
277	68	NOP
278	42	STO
279	20	20
280	68	NOP
281	53	(
282	43	RCL
283	19	19
284	65	×
285	43	RCL
286	20	20

287	75	-
288	01	1
289	54	)
290	65	×
291	53	(
292	01	1
293	85	+
294	43	RCL
295	15	15
296	54	)
297	65	×
298	53	(
299	01	1
300	85	+
301	53	(
302	43	RCL
303	15	15
304	65	×
305	43	RCL
306	09	09
307	65	×
308	43	RCL
309	03	03
310	54	)
311	55	÷
312	53	(
313	93	.
314	02	2
315	03	3
316	65	×
317	43	RCL
318	01	01
319	54	)
320	54	)
321	55	÷
322	53	(
323	43	RCL
324	20	20
325	65	×
326	53	(
327	43	RCL
328	19	19
329	75	-
330	01	1
331	54	)
332	95	=
333	34	ΓX
334	75	-
335	01	1
336	95	=
337	65	×
338	43	RCL
339	04	04
340	65	×
341	43	RCL
342	06	06
343	65	×
344	43	RCL
345	05	05
346	33	X^2
347	95	=
348	55	÷
349	03	3
350	02	2
351	93	.
352	01	1
353	07	7
354	95	=
355	99	PRT
356	61	GTO
357	10	E'
358	76	LBL
359	13	C
360	65	×
361	53	(
362	43	RCL
363	02	02
364	33	X^2
365	65	×
366	93	.
367	02	2
368	85	+
369	01	1
370	54	)
371	95	=
372	99	PRT
373	42	STO
374	01	01
375	61	GTO
376	04	04
377	45	45
378	65	×
379	93	.
380	02	2
381	85	+
382	01	1

```
383  95   =
384  35  1/X
385  65   ×
386  43  RCL
387  08   08
388  95   =
389  32  X:T
390  05   5
391  00   0
392  00   0
393  00   0
394  22  INV
395  77   GE
396  17  B'
397  32  X:T
398  99  PRT
399  43  RCL
400  15   15
401  99  PRT
402  43  RCL
403  17   17
404  34  √X
405  99  PRT
406  61  GTO
407  01   01
408  98   98
409  91  R/S
410  76  LBL
411  19  D'
412  09   9
413  09   9
414  09   9
415  09   9
416  99  PRT
417  91  R/S
418  76  LBL
419  10  E'
420  98  ADV
421  43  RCL
422  27   27
423  42  STO
424  15   15
425  25  CLR
426  69  OP
427  22   22
428  43  RCL
429  02   02
430  16  A'
431  91  R/S
432  68  NOP
433  68  NOP
434  68  NOP
435  68  NOP
436  68  NOP
437  76  LBL
438  16  A'
439  99  PRT
440  42  STO
441  02   02
442  43  RCL
443  25   25
444  13   C
445  25  CLR
446  43  RCL
447  02   02
448  65   ×
449  43  RCL
450  26   26
451  95   =
452  42  STO
453  05   05
454  99  PRT
455  43  RCL
456  27   27
457  42  STO
458  15   15
459  11   A
460  91  R/S
461  81  RST
462  76  LBL
463  14   D
464  65   ×
465  43  RCL
466  08   08
467  95   =
468  32  X:T
469  04   4
470  00   0
471  00   0
472  00   0
473  00   0
474  00   0
475  00   0
476  00   0
477  00   0
478  00   0
```

APPENDIX B

TI-59 SCRAMJET PROGRAM OUTPUT

Various scramjet parameters are presented for hypersonic flight at various altitudes from sea level to 150,000 feet.

Altitude (feet)	M_0	T_{T0} (°R)	V_0 (ft/sec)	T_5 (°R)	f	M_5	T_{T5} (°R)	T (lbf)
0	5	3112.13	5580	4051.94	0.0266	1.10	5024.32	17837.82
	6	4253.24	6696	4997.24	0.0376	1.38	6887.59	27256.33
	7	5601.83	7812	4976.24	0.0396	1.83	8319.59	29712.14
	8	7157.89	8928	4980.84	0.0411	2.23	9913.11	31697.62
	9	8921.43	10044	4992.14	0.0426	2.60	11701.04	33654.02
10,000	5	2898.16	5397	3761.02	0.0246	1.10	4676.10	12233.47
	6	3960.81	6476	4958.52	0.0371	1.28	6571.84	20070.64
	7	5216.68	7556	4953.15	0.0396	1.74	7949.12	22165.42
	8	6172.68	8298	4953.17	0.0411	2.13	9440.40	23605.33
	9	8308.05	9715	4967.43	0.0426	2.49	11112.72	25009.45
20,000	5	2684.21	5187	3466.42	0.0226	1.11	4325.52	8014.64
	6	3668.42	6224	4984.02	0.0366	1.13	6255.82	14223.52
	7	4831.57	7261	4992.22	0.0401	1.62	7612.03	16136.02
	8	6174.68	8299	4978.57	0.0416	2.01	9000.38	17150.71
	9	7694.73	9336	4991.95	0.0431	2.36	10556.30	18130.12
	10	9394.73	10373	4958.40	0.0441	2.71	12248.08	10044.38
30,000	5	2470.20	4973	3309.85	0.0211	1.03	4009.25	5235.26
	6	3375.94	5968	4743.11	0.0341	1.06	5802.09	9245.33
	7	4446.36	6963	4991.60	0.0401	1.50	7241.67	11322.25
	8	5681.46	7957	4959.58	0.0416	1.90	8527.83	12014.92
	9	7081.25	8952	4972.51	0.0431	2.24	9968.16	12677.54
	10	8645.71	9947	4989.23	0.0446	2.57	11562.01	13323.02

Altitude (feet)	M_0	T_{T0} (°R)	V_0 (ft/sec)	T_5 (°R)	f	M_5	T_{T5} (°R)	T (lbf)
40,000	5	2339.93	4843	3032.62	0.0196	1.11	3774.17	3177.28
	6	3197.90	5811	4473.08	0.0321	1.07	5491.71	5693.92
	7	4211.87	6780	4942.83	0.0396	1.44	6982.58	7345.04
	8	5381.83	7748	4951.35	0.0416	1.82	8240.16	7896.57
	9	6707.79	8717	4962.45	0.0431	2.16	9610.14	8323.30
50,000	5	2339.93	4840	3023.62	0.0196	1.11	3774.17	1958.56
	6	3197.90	5808	4473.08	0.0321	1.07	5491.71	3509.87
	7	4211.87	6777	4942.83	0.0396	1.44	6982.58	4527.66
	8	5381.83	7745	4951.35	0.0416	1.82	8240.16	4867.64
	9	6707.79	8713	4962.45	0.0431	2.16	9610.14	5130.69
	10	8189.75	9681	4981.58	0.0446	2.48	11125.52	5384.73
60,000	5	2339.93	4840	3032.62	0.0196	1.11	3774.17	1215.46
	6	3197.90	5808	4473.08	0.0321	1.07	5491.71	2178.20
	7	4211.87	6776	4942.83	0.0396	1.44	6982.58	2809.83
	8	5381.98	7744	4951.35	0.0416	1.82	8240.16	3020.81
	9	6707.79	8712	4962.45	0.0431	2.16	9610.14	3184.06
80,000	5	2339.93	4840	3032.62	0.0196	1.11	3774.17	464.24
	6	3197.90	5808	4473.08	0.0321	1.07	5491.71	831.95
	7	4211.87	6776	4942.83	0.0396	1.44	6982.58	1073.90
	8	5381,83	7744	4951.35	0.0416	1.82	8240.16	1153.78
	9	6707.79	8712	4962.45	0.0431	2.16	9610.14	1216.13
100,000	5	2517.48	5025	3247.16	0.0211	1.12	4055.55	182.82
	6	3440.56	6030	4775.08	0.0346	1.08	5898.92	328.61
	7	4531.46	7035	4990.11	0.0401	1.52	7323.49	396.20
	8	5790.20	8040	4963.27	0.0416	1.92	8632.22	420.59
	9	7216.78	9045	4976.52	0.0431	2.27	10098.09	443.96
	10	8811.18	10050	4992.24	0.0446	2.60	11720.42	466.80

Altitude (feet)	M_0	T_{T0} (°R)	V_0 (ft/sec)	T_5 (°R)	f	M_5	T_{T5} (°R)	T (lbf)
150,000	5	3011.26	5490	3902.20	0.0256	1.11	4856.84	24.72
	6	4115.38	6588	4941.18	0.0371	1.34	6720.88	38.81
	7	5420.26	7686	4964.63	0.0396	1.79	8144.94	42.91
	8	6925.89	8784	4967.47	0.0411	2.18	9690.26	45.74
	9	8632.27	9882	4980.29	0.0426	2.54	11423.69	48.52
	10	10539.40	10980	4984.97	0.0441	2.90	13344.40	51.31

APPENDIX C
GUN-LAUNCHED SCRAMJET/ROCKET ASAT MISSION PROFILE, PROGRAM LISTING

```
1 REM THIS PROGRAM WILL CALCULATE THE FLIGHT PATH FOR A 16", GUN-LAUNCHED ROCKET
2 REM OR SCRAMJET VEHICLE FOR USE IN AN ANTI-SATELLITE MISSION.  FLAT EARTH
3 REM TRAJECTORY IS ASSUMED.
4 REM FOR A SINGLE RUN WITH OUTPUT EVERY 10 SECONDS, ENTER RUN.
5 REM FOR A PROGRAM THAT WILL CALCULATE APOGEE FOR GUN ELEVATON ANGLES,(15-45)
6 REM DEG, ANGLE OF ATTACK,(0-12) DEG., AND POP-UP ALTITUDE,(100-11500) METERS,
7 REM RUN, DRAW THE AXISES THEN CONTINUE AT LINE 20.
8 REM----------------------------------------------------------------------
10 GOTO 200
15 REM -------------FOR  APOGEE RUN W8=0(SCRAMJET),W8=1(ROCKET).--------------
20 W8=0
30 W9=1
40 A7=-3
50 H1=0
60 A4=A=45
70 G9=0
80 H1=H1+100
90 PEN
100 IF H1>11500 THEN 2180
110 A7=A7+3
120 A=A4
130 IF A7<15 THEN 450
140 A7=3
150 A=A4=A4-5
160 IF A>10 THEN 450
170 A4=A=45
180 A7=0
190 GOTO 80
195 REM -----------AXIS SIZING--------------------------------------------
200 X9=66666.667
210 Y9=66666.667
```

```
220 PRINT "HAVE THE AXES BEEN DRAWN?"
230 PRINT ""
240 DISP "YES=1,NO=0";
250 INPUT Z8
260 IF Z8=1 THEN 450
270 SCALE 0,3*X9,0,3*Y9
280 XAXIS 0,X9/10,0,3*X9
290 YAXIS 0,Y9/10,0,3*Y9
300 REM-------------INPUT ROUTINE-----------------------------------------------
310 DISP "INPUT GUN ELEVATION ANGLE,0-45 (DEG).";
320 WAIT 100
330 INPUT A
340 DISP "INPUT POP-UP ALT(M)";
350 WAIT 100
360 INPUT H1
370 DISP "INPUT ANGLE OF ATTACK (DEG).";
380 WAIT 100
390 INPUT A7
400 PRINT "ROCKET (INPUT(1)); SCRAMJET (INPUT(0))"
410 PRINT ":::::::::::::::::::::::::::::::::::::::::::::::::::::::::"
420 INPUT W8
425 REM-------------PROGRAM INITIALIZATIION-------------------------------------
430 G9=10
440 W9=0
450 J=0
460 A3=10
470 R9=0.4572
480 L9=3
490 A8=80
500 M3=45
510 FORMAT 5F14.3
520 T=1
530 DEG
540 X8=1
550 X3=1
560 Y8=1
```

```
570 X1=X8
580 Y1=Y8
590 M7=0
600 M2=M=4.5
610 A2=360
620 V1=M2*A2
630 A9=0.1297
640 A0=0.0993
650 R0=0.3556
660 R7=1-(R0/R9)↑2
670 M1=325
680 M6=M1
690 G1=1.4
700 R=1.22642
710 H=7620
720 G=9.807
730 U=V1*COSA
740 V=V1*SINA
750 Q1=(1/2)*R*(V↑2+U↑2)*EXP(-Y1/H)
755 REM-------------INPUT ECHO-----------------------------------------------
760 IF W8>0 THEN 2200
770 IF W9=1 THEN 850
780 DISP "WANT PRINT OF INPUT YES=1 NO=0";
790 INPUT W7
800 IF W7<1 THEN 850
810 PRINT "ELEVATION ANGLE=";A"POP-UP ALT=";H1
820 PRINT "ANGLE OF ATTACK=";A7"FUEL(KG)=";M3
830 PRINT "MAXF.P.ANGLE=";A8" DELTA TIME=";T
840 PRINT "INLET AREA(M↑2)=";A0
850 V8=V1*SINA
860 U8=V1*COSA
870 PLOT X1,Y1
880 X2=X3=X1+U*T
890 Y2=Y3=Y1+V*T
900 T1=T
910 PLOT X2,Y2
920 IF W9=1 THEN 1000
```

```
925 REM-------------OUTPUT FORMAT----------------------------------------------
930 PRINT "**************************************************************"
940 PRINT "        ELAPSED        MACH        DRAG         ANGLE         THRUST"
950 PRINT "        TIME                                                        "
970 PRINT "--------------------------------------------------------------"
980 PRINT "        LIFT      VELOCITY           MASS      DYN PRESS          ALT"
990 PRINT "****************************************************************"
1000 GOTO 1400
1010 Y3=(-G+(F*SIN(A+A7)+L*COSA-D*SINA)/M6)*(T↑2)+2*Y2-Y1
1020 X3=(F*COS(A+A7)-L*SINA-D*COSA)*(T↑2)/M6+2*X2-X1
1030 PLOT X3,Y3
1040 T1=T1+T
1050 IF W8>0 THEN 2350
1055 REM------------SCRAMJET PAYLOAD SEPARATION---------------------------------
1060 IF Y3<150000 THEN 1100
1070 M6=30
1080 GOTO 1130
1090 IF M3=0 THEN 1130
1095 REM-----------------------------------------------------------------------
1100 M7=M7+W
1110 M6=M1-M7
1120 M3=M3-W
1130 U=(X3-X2)/T
1140 V=(Y3-Y2)/T
1145 REM------------APOGEE TEST--------------------------------------------------
1150 IF (Y3-Y2)<0 THEN 2570
1155 REM------------FLIGHT PATH ANGLE(A9), DYN.PRESS.(Q1), MACH #(M)------------
1160 A=ATN((Y3-Y2)/(X3-X2))
1170 Q1=(1/2)*R*(V↑2+U↑2)*EXP(-Y3/H)
1180 M8=(U↑2+V↑2)/(A2↑2)
1190 M=SQR(M8)
```

```
1195 REM-----------------------------------------------------------------------
1200 J=J+1
1210 IF W9=0 THEN 1240
1220 IF Y3>100000 THEN 1300
1230 GOTO 1360
1240 IF J=1 THEN 1300
1250 IF J=5 THEN 1300
1260 J1=INT(J/10)
1270 J2=(J/10)-J1
1280 IF J2=0 THEN 1300
1290 GOTO 1360
1300 V2=SQR(U↑2+V↑2)
1310 IF W9=1 THEN 1750
1320 WRITE (15,510)T1,M,D,A,F
1330 WRITE (15,510)L,V2,M6,Q1,Y3
1340 PRINT "**************************************************************"
1350 IF W9=1 THEN 90
1360 X1=X2
1370 Y1=Y2
1380 X2=X3
1390 Y2=Y3
1395 REM-----------IF VEHICLE IS ROCKET  CONT AT SONIC SPEED ROUTINE-----------
1400 IF W8>0 THEN 1580
1405 REM------------IF MORE THAN 1 KG. OF FUEL CALL SCRAMJET THRUST ROUTINE-----
1410 IF M3>1 THEN 2600
1420 F=0
1490 IF Y3>10970 THEN 1550
1495 REM------------FUEL FLOW ROUTINE FOR SCRAMJET-----------------------------
1500 IF M>6 THEN 1530
1510 F8=0.0226+0.011*(M-5)
1520 GOTO 1580
1530 F8=0.037+0.00177*(M-6)
1540 GOTO 1580
1550 IF M>7 THEN 1530
1560 F8=0.021+0.0093*(M-5)
1570 GOTO 1580
```

```
1575 REM-----------SPEED OF SOUND AS A FUNCTION OF ALT.(M/SEC)-----------------
1580 IF Y3>11000 THEN 1620
1590 A2=360-0.006363*Y3
1600 IF W8>0 THEN 1740
1610 GOTO 1640
1620 A2=290
1630 IF W8>0 THEN 1890
1640 W0=A0*R*M*A2*EXP(-Y3/H)
1650 W=F8*W0
1660 GOTO 1890
1665 REM-----------SRCAMJET CONDTION POST FUEL EXHAUSTION----------------------
1670 R9=0.3556
1680 A9=A0
1690 F=0
1700 W=0
1710 F8=0
1720 R0=0
1730 R7=1-(R0/R9)↑2
1740 GOTO 1890
1745 REM-----------OUTPUT FOR APOGEE PROGRAM MODE-------------------------------
1750 Y5=Y3+(V↑2/(2*G))
1760 IF G9=1 THEN 1820
1770 PRINT "-------------------------------------------------------------------"
1780 PRINT "TR.AL           M#              VEL(M/S)        G.EL  <AT   TALT"
1790 PRINT "MAX.ALT(M)----------------------------------------------------------"
1800 PRINT "--------------------------------------------------------------------"
1810 G9=1
1820 PRINT A;M;V2;A4;A7;H1;Y5
1830 PRINT "--------------------------------------------------------------------"
1840 GOTO 1350
1850 GOTO 1890
1860 IF W8=0 THEN 1890
1870 IF J9=0 THEN 1890
1880 A7=0
```

```
1885 REM----------HYPERSONIC AERODYNAMICS----------------------------------------
1890 IF Y3<H1 THEN 2070
1900 IF A>A8 THEN 2070
1910 IF A7>A3 THEN 1950
1920 L2=R7*(COSA)↑2*SIN(2*A7)
1930 L3=(R7*(2*(SINA3)↑2+(SINA7)↑2*(1-3*(SINA3)↑2)))
1940 GOTO 2020
1950 P8=0.01745*ATN(TANA3/(SQR((TANA7)↑2-(TANA3)↑2)))
1960 L2=(COSA3)↑2*SIN(2*A7)*((P8+1.57)/3.14)+0.0161*COS(P8*57.29578)
1970 L2=L2*((COSA7/SINA7)*TANA3+2*TANA7*(COSA3/SINA3))
1980 L2=L2*R7
1990 L3=((P8+1.57)/3.14)*(2*(SINA3)↑2+(SINA7)↑2*(1-3*(SINA3)↑2))
2000 L3=L3+0.2387*COS(P8*57.29578)*SIN(2*A7)*SIN(2*A3)
2010 L3=L3*R7
2020 L5=L2*SINA7+L3*COSA7
2030 L6=L2*COSA7-L3*SINA7
2040 L7=1.69765*(L9/R9)*(SINA7)↑2*COSA7
2050 L8=1.69765*(L9/R9)*(SINA7)↑2*SINA7
2060 GOTO 2090
2070 L5=R7*2*(SINA3)↑2
2080 L6=L7=L8=0
2090 C=L5+L8
2100 C6=L6+L7
2110 L=C6*A9*Q1
2120 GOTO 2430
2130 D=Q1*A9*C+D6
2140 C2=C
2170 GOTO 1010
```

```
2175 REM-----------ROCKET INITIALIZATION--------------------------------------
2200 A3=10.5
2210 R9=0.4191
2220 R0=0
2230 A0=0
2240 M1=345
2250 M2=M=4.5
2260 M3=216
2270 F=84556.5
2280 W=36
2290 J9=0
2300 L9=2.9432
2310 V1=M2*A2
2320 U=V1*COSA
2330 V=V1*SINA
2340 GOTO 770
2345 REM-----------ROCKET CONDITON POST FUEL EXHAUSTION------------------------
2350 IF M3=0 THEN 2370
2360 GOTO 2400
2370 F=0
2380 W=0
2390 GOTO 2400
2395 REM ----------ROCKET PAYLOAD SEPARATION------------------------------------
2400 IF Y3<150000 THEN 1090
2410 M6=30
2420 GOTO 1090
```

```
2425 REM-----------SKIN FRICTION DRAG----------------------------------------
2430 IF Y3>11000 THEN 2460
2440 U9=(Y3/-2.997E+09)+1.789E-05
2450 GOTO 2530
2460 IF Y3>25000 THEN 2490
2470 U9=1.422E-05
2480 GOTO 2530
2490 IF Y3>75000 THEN 2520
2500 U9=((Y3-25000)/-3.873E+09)+1.422E-05
2510 GOTO 2530
2520 U9=1.336E-06
2530 C7=1.328/SQR((EXP(-Y3/H)*(M*A2)*L9)/U9)
2540 D6=Q1*6.283*(R9/2)*L9*C7
2550 IF L=0 THEN 2560
2560 GOTO 2130
2565 REM-----------APOGEE FAULT---------------------------------------------
2570 PRINT "FALLING OUT OF SKY";" ALT=";Y3"RNG=";X3"A="A
2580 PRINT "GUN.EL="A4,"ALFA="A7,"TALT="H1
2590 GOTO 90
2595 REM-----------SCRAMJET THRUST -----------------------------------------
2600 IF Y3>3048 THEN 2690
2610 IF M>6 THEN 2640
2620 F=(9500-Y3*0.5577)*(M-5)+17800-1.837*Y3
2630 GOTO 3100
2640 IF M>7 THEN 2670
2650 F=2133*(M-6)+27300-2.395*Y3
2660 GOTO 3100
2670 F=(2133-Y3*0.2241)*(M-7)+29700-2.49*Y3
2680 GOTO 3100
2690 IF Y3>6096 THEN 2780
2700 IF M>6 THEN 2730
2710 F=(7800-(Y3-3048)*0.5249)*(M-5)+12200-1.4*(Y3-3048)
2720 GOTO 3100
2730 IF M >= 7 THEN 2760
2740 F=(2100-(Y3-3048)*0.0656)*(M-6)+18800-1.9*(Y3-3804)
2750 GOTO 3100
2760 F=(1450-(Y3-3048)*0.1696)*(M-7)+21000-2.034*(Y3-3804)
2770 GOTO 3100
```

```
2780 IF Y3>9144 THEN 2870
2790 IF M>6 THEN 2820
2800 F=(6200-(Y3-6096)*0.72178)*(M-5)+8000-0.919*(Y3-6096)
2810 GOTO 3100
2820 IF M>7 THEN 2850
2830 F=(1900-(Y3-6096)*0.06562)*(M-6)+14200-1.64*(Y3-6096)
2840 GOTO 3100
2850 F=(933-(Y3-6096)*0.08737)*(M-7)+16100-1.57*(Y3-6096)
2860 GOTO 3100
2870 IF Y3>12192 THEN 2960
2880 IF M>6 THEN 2910
2890 F=(4000-(Y3-9144)*0.4921)*(M-5)+5200-0.656*(Y3-9144)
2900 GOTO 3100
2910 IF M >= 7 THEN 2940
2920 F=(2100-(Y3-9144)*0.164)*(M-6)+9900-1.4*(Y3-9144)
2930 GOTO 3100
2940 F=666.7*(M-7)+11300-1.31*(Y3-9144)
2950 GOTO 3100
2960 IF Y3>15240 THEN 3050
2970 IF M>6 THEN 3000
2980 F=(2500-(Y3-12192)*0.3281)*(M-5)+3200-0.3937*(Y3-12192)
2990 GOTO 3100
3000 IF M>7 THEN 3030
3010 F=(1600-(Y3-12192)*0.19685)*(M-6)+5700-0.72178*(Y3-12192)
3020 GOTO 3100
3030 F=(500-(Y3-12192)*0.0164)*(M-7)+7300-0.9186*(Y3-12192)
3040 GOTO 3100
3050 IF M>6 THEN 3080
3060 F=(17800+9500*(M-5))*EXP(-Y3/H)
3070 GOTO 3100
3080 F=(27300+2133*(M-6))*EXP(-Y3/H)
3090 GOTO 3100
3100 F=4.45*F*(A0/0.111)
3110 GOTO 1490
3120 STOP
```

APPENDIX D

GUN-LAUNCHED SCRAMJET ASAT APOGEE AS A FUNCTION OF GUN ELEVATION, ANGLE OF ATTACK AND POP-UP ALTITUDE

Gun Elevation (DEG)	Angle of Attack (DEG)	Pop-up Altitude (m)	Apogee (Km)
30	0	0	123
35	0	0	169
40	0	0	214
45	0	0	239
15	3	500	162
20	3	500	186
25	3	500	209
30	3	500	236
35	3	500	265
40	3	500	275
45	3	500	286
15	3	1000	161
20	3	1000	165
25	3	1000	208
30	3	1000	228
35	3	1000	258
40	3	1000	275
45	3	1000	302
15	3	1500	135
20	3	1500	162
25	3	1500	188
30	3	1500	228
35	3	1500	258
40	3	1500	272
45	3	1500	282
15	3	3000	127
20	3	3000	155
25	3	3000	184
30	3	3000	219
35	3	3000	249
40	3	3000	270
45	3	3000	280

Gun Elevation (DEG)	Angle of Attack (DEG)	Pop-up Altitude (m)	Apogee (Km)
25	3	6000	168
30	3	6000	197
35	3	6000	233
40	3	6000	265
45	3	6000	274
20	3	9000	114
25	3	9000	157
30	3	9000	183
35	3	9000	223
40	3	9000	257
45	3	9000	269
25	3	11000	142
30	3	11000	178
35	3	11000	219
40	3	11000	254
45	3	11000	267
15	6	500	305
20	6	500	329
25	6	500	343
30	6	500	334
35	6	500	330
40	6	500	328
45	6	500	329
15	6	1000	227
20	6	1000	314
25	6	1000	330
30	6	1000	337
35	6	1000	332
40	6	1000	328
45	6	1000	329
15	6	1500	276
20	6	1500	294
25	6	1500	318
30	6	1500	337
35	6	1500	332
40	6	1500	329
45	6	1500	326

Gun Elevation (DEG)	Angle of Attack (DEG)	Pop-up Altitude (m)	Apogee (Km)
15	6	3000	269
20	6	3000	256
25	6	3000	302
30	6	3000	321
35	6	3000	331
40	6	3000	327
45	6	3000	326
15	6	6000	188
20	6	6000	228
25	6	6000	253
30	6	6000	287
35	6	6000	308
40	6	6000	317
45	6	6000	316
15	6	9000	133
20	6	9000	196
25	6	9000	229
30	6	9000	321
35	6	9000	283
40	6	9000	300
45	6	9000	303
15	6	11000	115
20	6	11000	164
25	6	11000	201
30	6	11000	245
35	6	11000	272
40	6	11000	293
45	6	11000	297
15	9	500	409
20	9	500	380
25	9	500	368
30	9	500	355
35	9	500	345
40	9	500	341
45	9	500	333

Gun Elevation (DEG)	Angle of Attack (DEG)	Pop-up Altitude (m)	Apogee (Km)
15	9	1000	403
20	9	1000	405
25	9	1000	387
30	9	1000	374
35	9	1000	362
40	9	1000	360
45	9	1000	333
15	9	1500	345
20	9	1500	404
25	9	1500	403
30	9	1500	374
35	9	1500	360
40	9	1500	350
45	9	1500	344
15	9	3000	341
20	9	3000	360
25	9	3000	389
30	9	3000	389
35	9	3000	370
40	9	3000	358
45	9	3000	348
15	9	6000	304
20	9	6000	288
25	9	6000	342
30	9	6000	368
35	9	6000	361
40	9	6000	358
45	9	6000	349
15	9	9000	249
20	9	9000	249
25	9	9000	285
30	9	9000	321
35	9	9000	339
40	9	9000	341
45	9	9000	332

Gun Elevation (DEG)	Angle of Attack (DEG)	Pop-up Altitude (m)	Apogee (Km)
15	9	11000	209
20	9	11000	210
25	9	11000	269
30	9	11000	308
35	9	11000	321
40	9	11000	330
45	9	11000	325
15	12	500	414
20	12	500	360
25	12	500	317
30	12	500	346
35	12	500	339
40	12	500	293
45	12	500	335
15	12	1000	463
20	12	1000	398
25	12	1000	379
30	12	1000	349
35	12	1000	361
40	12	1000	293
45	12	1000	335
15	12	1500	478
20	12	1500	479
25	12	1500	408
30	12	1500	349
35	12	1500	361
40	12	1500	352
45	12	1500	337
15	12	3000	509
20	12	3000	465
25	12	3000	439
30	12	3000	411
35	12	3000	372
40	12	3000	365
45	12	3000	355

Gun Elevation (DEG)	Angle of Attack (DEG)	Pop-up Altitude (m)	Apogee (Km)
15	12	6000	558
20	12	6000	445
25	12	6000	426
30	12	6000	405
35	12	6000	402
40	12	6000	375
45	12	6000	361
15	12	9000	392
20	12	9000	442
25	12	9000	416
30	12	9000	419
35	12	9000	405
40	12	9000	379
45	12	9000	360
15	12	11000	332
20	12	11000	401
25	12	11000	411
30	12	11000	406
35	12	11000	397
40	12	11000	377
45	12	11000	360

APPENDIX E

MAXIMUM APOGEE TRAJECTORY, LISTINGS

Units:

Time = Seconds
Velocity = Meters/Second
Lift
Drag — Newtons
Thrust
Mass = KG
Altitude = Meters
Dynamic Pressure = Newton/Meter^2
Angle = Degrees

I. SCRAMJET

```
ELEVATION ANGLE= 15   POP-UP ALT= 6000
ANGLE OF ATTACK= 12   FUEL(KG)= 45
MAXF.P.ANGLE= 80     DELTA TIME= 1
INLET AREA(M↑2)= 0.0993
*****************************************************************
*****************************************************************
       ELAPSED        MACH         DRAG          ANGLE          THRUST
       TIME
-----------------------------------------------------------------
       LIFT        VELOCITY           MASS      DYN PRESS          ALT
*****************************************************************
        2.000         4.895       5546.445         15.724    49344.343
        0.000      1749.046        321.831    1668181.437      894.279
```

6.000	7.683	8136.645	19.990	88628.609
0.000	2626.330	297.923	2585927.279	3749.368
11.000	10.158	102462.196	79.829	0.000
362367.489	3272.111	275.249	1149956.524	13274.794
21.000	9.881	261.729	86.065	0.000
0.000	3183.084	275.249	15943.447	45456.046
31.000	9.571	6.548	85.940	0.000
0.000	3083.169	275.249	249.275	76655.847
41.000	9.267	0.472	85.806	0.000
0.000	2985.287	275.249	4.432	106870.276
51.000	8.964	0.059	85.664	0.000
0.000	2887.482	275.249	0.089	136103.791
61.000	8.660	0.009	85.512	0.000
0.000	2789.700	30.000	0.002	164356.574
71.000	8.357	0.001	85.348	0.000
0.000	2691.941	30.000	0.000	191628.634
81.000	8.053	0.000	85.173	0.000
0.000	2594.206	30.000	0.000	217919.990
91.000	7.750	0.000	84.983	0.000
0.000	2496.497	30.000	0.000	243230.644
101.000	7.447	0.000	84.779	0.000
0.000	2398.818	30.000	0.000	267560.598
111.000	7.144	0.000	84.556	0.000
0.000	2301.172	30.000	0.000	290909.853
121.000	6.841	0.000	84.314	0.000
0.000	2203.564	30.000	0.000	313278.407

131.000	6.538	0.000	84.050	0.000
0.000	2165.999	30.000	0.000	334666.261
141.000	6.235	0.000	83.760	0.000
0.000	2008.483	30.000	0.000	355073.415
151.000	5.932	0.000	83.440	0.000
0.000	1911.024	30.000	0.000	374499.870
161.000	5.630	0.000	83.087	0.000
0.000	1813.631	30.000	0.000	392945.624
171.000	5.328	0.000	82.692	0.000
0.000	1716.314	30.000	0.000	410410.678
181.000	5.026	0.000	82.251	0.000
0.000	1619.089	30.000	0.000	426895.032
191.000	4.725	0.000	81.753	0.000
0.000	1521.972	30.000	0.000	442398.687
201.000	4.424	0.000	81.188	0.000
0.000	1424.985	30.000	0.000	456921.641
211.000	4.123	0.000	80.540	0.000
0.000	1328.158	30.000	0.000	470463.895
221.000	3.823	0.000	79.790	0.000
0.000	1231.527	30.000	0.000	483025.449
231.000	3.524	0.000	78.912	0.000
0.000	1135.144	30.000	0.000	494606.304

241.000	3.226	0.000	77.872	0.000
0.000	1039.075	30.000	0.000	505206.458
251.000	2.929	0.000	76.621	0.000
0.000	943.419	30.000	0.000	514825.912
261.000	2.633	0.000	75.088	0.000
0.000	848.315	30.000	0.000	523464.667
271.000	2.341	0.000	73.169	0.000
0.000	753.970	30.000	0.000	531122.721
281.000	2.051	0.000	70.706	0.000
0.000	660.711	30.000	0.000	537800.075
291.000	1.767	0.000	67.442	0.000
0.000	569.072	30.000	0.000	543496.730
301.000	1.490	0.000	62.947	0.000
0.000	479.982	30.000	0.000	548212.684
311.000	1.227	0.000	56.466	0.000
0.000	395.168	30.000	0.000	551947.938
321.000	0.987	0.000	46.658	0.000
0.000	318.070	30.000	0.000	554702.492
331.000	0.794	0.000	31.400	0.000
0.000	255.762	30.000	0.000	556476.347
341.000	0.686	0.000	9.156	0.000
0.000	221.123	30.000	0.000	557269.501
351.000	0.705	0.000	-16.070	0.000
0.000	227.183	30.000	0.000	557081.955

```
*************************************************************
      361.000        0.842        0.000      -36.401          0.000
        0.000      271.228       30.000        0.000     555913.710
*************************************************************
      371.000        1.052        0.000      -49.876          0.000
        0.000      338.751       30.000        0.000     553764.764
*************************************************************
      381.000        1.299        0.000      -58.561          0.000
        0.000      418.539       30.000        0.000     550635.118
*************************************************************
      391.000        1.567        0.000      -64.377          0.000
        0.000      504.811       30.000        0.000     546524.773
*************************************************************
      401.000        1.846        0.000      -68.466          0.000
        0.000      594.750       30.000        0.000     541433.727
*************************************************************
      411.000        2.132        0.000      -71.470          0.000
        0.000      686.919       30.000        0.000     535361.981
*************************************************************
      421.000        2.423        0.000      -73.758          0.000
        0.000      780.527       30.000        0.000     528309.535
*************************************************************
      431.000        2.717        0.000      -75.554          0.000
        0.000      875.113       30.000        0.000     520276.390
*************************************************************
```

II. ROCKET

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ELEVATION ANGLE= 45   POP-UP ALT= 100
ANGLE OF ATTACK= 12   FUEL(KG)= 216
MAXF.P.ANGLE= 80    DELTA TIME= 1
INLET AREA(M↑2)= 0
```

ELAPSED TIME / LIFT	MACH / VELOCITY	DRAG / MASS	ANGLE / DYN PRESS	THRUST / ALT
2.000	5.179	49689.673	65.178	84556.500
189467.605	1826.784	309.000	1416255.808	2804.536
6.000	10.090	4532.344	86.939	84556.500
0.000	3007.758	165.000	1043213.958	12733.293
11.000	14.661	1155.192	81.846	0.000
0.000	4251.735	129.000	146255.136	32979.430
21.000	14.277	11.276	81.654	0.000
0.000	4140.308	129.000	603.747	74408.147
31.000	13.942	0.397	81.452	0.000
0.000	4043.131	129.000	2.860	114832.022
41.000	13.607	0.028	81.240	0.000
0.000	3946.168	30.000	0.015	154274.751
51.000	13.273	0.002	81.018	0.000
0.000	3849.268	30.000	0.000	192736.731
61.000	12.939	0.000	80.784	0.000
0.000	3752.431	30.000	0.000	230218.001
71.000	12.606	0.000	80.538	0.000
0.000	3655.661	30.000	0.000	266718.571

```
************************************************************
      81.000        12.272         0.000        80.279         0.000
       0.000      3558.961        30.000         0.000    302238.440
************************************************************
      91.000        11.939         0.000        80.004         0.000
       0.000      3462.339        30.000         0.000    336777.610
************************************************************
     101.000        11.606         0.000        79.715         0.000
       0.000      3365.801        30.000         0.000    370336.079
************************************************************
     111.000        11.274         0.000        79.408         0.000
       0.000      3269.354        30.000         0.000    402913.849
************************************************************
     121.000        10.941         0.000        79.082         0.000
       0.000      3173.006        30.000         0.000    434510.919
************************************************************
     131.000        10.610         0.000        78.736         0.000
       0.000      3076.767        30.000         0.000    465127.288
************************************************************
     141.000        10.278         0.000        78.368         0.000
       0.000      2980.648        30.000         0.000    494762.958
************************************************************
     151.000         9.947         0.000        77.975         0.000
       0.000      2884.659        30.000         0.000    523417.928
************************************************************
     161.000         9.617         0.000        77.556         0.000
       0.000      2788.816        30.000         0.000    551092.197
************************************************************
     171.000         9.287         0.000        77.106         0.000
       0.000      2693.133        30.000         0.000    577785.767
************************************************************
     181.000         8.957         0.000        76.623         0.000
       0.000      2597.628        30.000         0.000    603498.637
************************************************************
     191.000         8.629         0.000        76.104         0.000
       0.000      2502.322        30.000         0.000    628230.806
************************************************************
```

201.000	8.301	0.000	75.543	0.000
0.000	2407.237	30.000	0.000	651982.276
211.000	7.974	0.000	74.937	0.000
0.000	2312.402	30.000	0.000	674753.046
221.000	7.648	0.000	74.278	0.000
0.000	2217.848	30.000	0.000	696543.115
231.000	7.323	0.000	73.561	0.000
0.000	2123.613	30.000	0.000	717352.485
241.000	6.999	0.000	72.778	0.000
0.000	2029.742	30.000	0.000	737181.155
251.000	6.677	0.000	71.919	0.000
0.000	1936.287	30.000	0.000	[illegible]
261.000	6.356	0.000	70.972	0.000
0.000	1843.311	30.000	0.000	773896.394
271.000	6.038	0.000	69.926	0.000
0.000	1750.891	30.000	0.000	790782.964
281.000	5.721	0.000	68.764	0.000
0.000	1659.121	30.000	0.000	806688.834
291.000	5.407	0.000	67.465	0.000
0.000	1568.113	30.000	0.000	821614.003
301.000	5.097	0.000	66.008	0.000
0.000	1478.008	30.000	0.000	835558.473
311.000	4.790	0.000	64.363	0.000
0.000	1388.984	30.000	0.000	848522.243

```
-***********************************************************
    321.000       4.487       0.000      62.495       0.000
      0.000    1301.260      30.000       0.000  860505.312
***********************************************************
    331.000       4.190       0.000      60.359       0.000
      0.000    1215.120      30.000       0.000  871507.682
***********************************************************
    341.000       3.900       0.000      57.900       0.000
      0.000    1130.924      30.000       0.000  881529.352
***********************************************************
    351.000       3.618       0.000      55.053       0.000
      0.000    1049.141      30.000       0.000  890570.322
***********************************************************
    361.000       3.346       0.000      51.735       0.000
      0.000     970.382      30.000       0.000  898630.591
***********************************************************
    371.000       3.088       0.000      47.845       0.000
      0.000     895.445      30.000       0.000  905710.161
***********************************************************
    381.000       2.846       0.000      43.272       0.000
      0.000     825.370      30.000       0.000  911809.031
***********************************************************
    391.000       2.626       0.000      37.891       0.000
      0.000     761.503      30.000       0.000  916927.200
***********************************************************
    401.000       2.433       0.000      31.593       0.000
      0.000     705.530      30.000       0.000  921064.670
***********************************************************
    411.000       2.274       0.000      24.316       0.000
      0.000     659.465      30.000       0.000  924221.440
***********************************************************
    421.000       2.157       0.000      16.101       0.000
      0.000     625.500      30.000       0.000  926397.509
***********************************************************
    431.000       2.089       0.000       7.152       0.000
      0.000     605.675      30.000       0.000  927592.879
***********************************************************
```

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